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EDITED BY

JOSEPH M. JAMESON

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HEAT

A MANUAL FOR TECHNICAL
AND INDUSTRIAL STUDENTS

BY

J. A. RANDALL

Pratt Institute

FIRST EDITION, CORRECTED

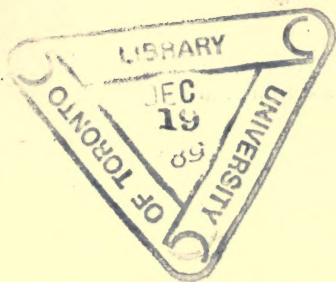
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PREFACE

THIS text is intended to set forth briefly the essential principles of heat. The idea of heat as a form of molecular energy is first made clear. The production, the measurement, the transmission, and the effects of heat are then discussed. In Chapters V and VIII particular attention is given to a clear and direct development of the continuity of state, and, in the case of the gaseous state, to the temperature—pressure—volume—energy relations which have a technical application. Care is taken to make the treatment progress slowly enough to make the definitions and the measuring of the physical constants clear. The matter is developed with sufficient rapidity and with enough continuity to give the reader a broad view of the subject as a whole. As a further illustration of the application of the laws of heat, and to give the student a conception of the use to which he should put his study, in Chapters VI, VII, and X, steam power plants, gas power plants, and refrigeration are discussed. The attempt is made rather to show the function of the essential members and the dependence of this function upon the fundamental laws of heat energy, than to give a technical discussion of such plants.

The author has here endeavored to furnish the general student or reader with such an insight into the nature of heat and its effects as shall enable him to comprehend, reasonably, the operation of various power processes with which he may come in contact. The book is also intended

to provide the student who will later take up technical questions involving the design and construction of power machinery with a background of understanding which shall enable him to more fully comprehend the problems with which he must deal and the fundamental heat considerations which are involved.

In the treatment of the material, the historical method has been discarded as requiring too much space as well as the introduction of material not essential to a mastery of the fundamental principles. Heat as energy, and the necessary processes and effects involved in the production, distribution, and utilization of this energy have been selected as the central themes. Thus around the energy theme the mass of supplementary material is grouped. This method of presentation has been followed for several years at Pratt Institute through the use of a set of mimeograph sheets from which this text has ultimately evolved. These sheets have also been issued for the past year in the form of a preprint and have secured successful results at Pratt Institute and at Wentworth Institute, Boston, Mass. The arrangement and selection of the material presented is that which has been shown to be suitable by the experience of the teachers who have been using these notes with several hundred students each year.

If any novelty may be ascribed to this text, it is to be found in the type of material used as a medium for the presentation of the fundamental facts and laws of heat, and in the manner in which this material is organized, rather than in the mere character of the facts themselves. In this latter respect, no particular attempt at originality has been made. The language is as simple as possible. Only such technical words and phrases are introduced as are necessary to enable the student to feel at home in a technical atmosphere, to understand the current technical literature of the subject, and to handle reference books with confidence. Little mathematics is required. A knowl-

edge of simple, algebraic equations is assumed, and in Chapter VIII, logarithms are used in one type of problem.

The numerous, carefully selected problems constitute what is believed to be one of the strongest features of the book. These involve the usual computations found in elementary text-books on heat. They also include a large number of problems dealing with the applications of heat to common processes which students observe daily, and which involve fundamental ideas of which the student ought to have an intelligent understanding. The number and the grading of these problems is such that supplementary drill either in theoretical heat or in technical heat may be readily given by the teacher in accordance with his needs.

Attention is called to the general plan of the text. This is such that the book may be used for either a very short course or as a basis for a long course taking four hours a week for a semester. For a short course, the fine print should be omitted and only Chapters I to V and selected sections of Chapter XI should be assigned. Thus, in ten lessons, a general course in theoretical heat with a brief suggestion of practical applications may be given. A longer course results by assigning all of the subject-matter, by selecting problems which have to do with the processes and principles involved, and by giving special attention to Chapters VI to X. Thus the text will furnish, it is believed, the basis for a satisfactory course in heat for those technical students who are later to go on to the study of the engineering phases of the subject.

Throughout the preparation of this work the author has been aided by the constructive criticism suggested by the experience of Mr. Jameson, Vice-President, Girard College, Philadelphia, and by his former associate, Mr. W. H. Timbie, Head of the Applied Science Department, Wentworth Institute, Boston, Mass. Thanks are also due to Prof. Harvey N. Davis, of Harvard University, to Prof.

H. H. Higbie, of University of Michigan, Ann Arbor, R. B. Brownlee, Stuyvesant High School, New York, and to Mr. J. P. Kottcamp, of Pratt Institute, for valued criticisms, also to Mr. F. A. Clark, of Pratt Institute, for proof-reading.

J. A. RANDALL.

BROOKLYN, N. Y., December, 1912.

EDITOR'S NOTE

THERE is at present no American text in Elementary Heat which emphasizes the applications of the fundamental principles of the subject to the various commercial and engineering processes in which they are the controlling factor. It is unfortunate that the student who takes up the study of Power Engineering should be poorly prepared in the subject most fundamental to his new undertaking. It is perhaps more unfortunate that students in elementary general courses in Heat should fail to be taught those conceptions which will enable them to deal most intelligently with the many problems in heating, ventilation, and the utilization of heat energy, which are commonly encountered in the ordinary affairs of domestic, business, and industrial life.

This little text is designed to meet the needs of the above two groups of students. The author has had long experience in teaching Heat to classes of technical students. As a university student he specialized in the subject upon which he has written, and since that time he has kept in close contact with the modern developments of Heat Engineering. The text will be found to be scholarly and in accordance with the terminology and usages of the best modern engineering practice.

THE EDITOR.

TABLE OF CONTENTS

CHAPTER I

ENERGY

PAGE

Forms of Energy.—Mechanical Energy.—Chemical Energy.— Electrical Energy.—Light Energy.—Heat Energy, its Nature. —Kinetic Theory.—Temperature.—Temperature Units.— Units of Quantity of Heat Energy.—Relation between Mechan- ical Energy Units, Heat Energy Units, and Electrical Energy Units.	1-26
--	------

CHAPTER II

ENERGY FROM FUELS

Fuels and their Analysis.—Air in Chemical Reactions.—Energy in all Chemical Reactions.—Heat Energy of Fuels.—Explo- sives.—Exceptional Fuels.—Purchasing Coal.—Heat Engines. —Power Plant.—Efficiency.	27-43
---	-------

CHAPTER III

SPECIFIC HEAT AND CALORIMETRY

Specific Heat.—Specific Heat not a Constant.—Calorimetry.— Method of Mixtures.—Water Equivalent.—Precautions in Calorimetry.—Other Methods.	44-63
---	-------

CHAPTER IV

EXPANSION

Expansion of Solids, Linear.—Coefficient of Expansion of an Area.—Coefficient of Cubical Expansion.—Expansion of	
---	--

Liquids.—Expansion of Gases.—Boyle's Law.—Charles' Law.—Pressure Effects Due to Change of Temperature of a Constant Volume.—Absolute Temperature.—Expansion with Three Variables.—Experiments on the Coefficient of Expansion of Air.—Expansion of Gases.—Boyle's and Charles' Law Combined.—Density and Volume Affected by Expansion.....	64-100
--	--------

CHAPTER V

THREE STATES OF MATTER

All Elements have Three States: Ice, Water, and Steam.—Latent Heat.—Definitions and Distinctions.—Dalton's Law.—Solutions and Mixtures.—Distillation.—Cooling Towers.—Analysis of Latent Heat of Vaporization.—Relation between the Pressure and the Temperature of Steam.—Experimental Determination of this Relation.—Steam Tables.—Superheated Steam.....	101-138
--	---------

CHAPTER VI

FUNCTION OF A STEAM POWER PLANT

A Simple Plant.—Effective Pressure.—Circulation of Water, Flue Gases, etc.—Energy Circulation.—Computation of Power.—Energy Utilization.—Steam Boiler.—Efficiency of the Boiler.—Water Rate.—Feed-water Heaters and Economizers.—Condensers.—Steam Engine Functions.—Rankine Cycle.....	139-177
---	---------

CHAPTER VII

FUNCTION OF A GAS POWER PLANT

Comparative Efficiency.—Fuels.—Carbureter.—Vaporizer.—Firing Systems.—Cycles.—Fuel Circulation in a Producer Gas Power Plant.—Energy Circulation.—Explosive Mixtures.—Working Medium.....	178-197
---	---------

CHAPTER VIII

EXPANSION OF GASES—*Continued*

PAGE

Specific Heat of a Gas: At Constant Volume; at Constant Pressure.—Isothermal Expansion.—Adiabatic Expansion.—Quantity of Energy in Gases.—Reversible Processes.—Entropy.....	198-222
--	---------

CHAPTER IX

CONVECTION, CONDUCTION, RADIATION, AND THE INSULATION OF BODIES

Convection of Heat Energy.—The Draft of a Chimney.—Conduction of Heat Energy.—Units and Computation of Conductance.—Insulation.—Radiation Laws.—Black Body Radiations.—Relation of Visible Radiations to Heat Radiations.—Insulating Devices.....	223-245
---	---------

CHAPTER X

FUNCTION OF THE REFRIGERATOR PLANT

Household Refrigeration.—Mechanical Refrigeration.—Energy Flow through a Compression Type Plant.—The Steam Cycle and the Ammonia Cycle Compared.—Computations.—The Absorption Plant.—Cryogenics.—Mechanical Production of Low Temperatures.—Insulation of Cold Storage Spaces..	246-267
---	---------

CHAPTER XI

INSTRUMENTS

Instruments for the Measurement of Temperature.—Mercury Thermometers, their Manufacture, and Purchase.—Construction of Mercury Thermometers.—Alcohol Thermometers.—Differential Thermometers.—Gas Thermometers.—Pyrometers.—The Bolometer.—Thermo-junction Pyrometers.—Heat Radiation Pyrometers.—Optical Pyrometers.—Fuel Calorimeters.—Steam Indicators.....	268-294
--	---------

APPENDIX A

TABLES

PAGE

Useful Numbers.—Relation between Units.—Heat Energy Developed by Oxidation.—Analysis of Various Coals.—Gas Analyses.—Specific Heat.—Coefficient of Expansion.—Melting-points, Boiling-points, and Latent Heats.—Steam Tables.—Pressure-Entropy Tables.—Specific Heat of Superheated Steam.—Wave Lengths of Various Waves.—Temperatures of Hot Bodies.—Conductances	295-307
--	---------

APPENDIX B

Barometer Corrections	308-309
---------------------------------	---------

APPENDIX C

Significant Figures	310-313
-------------------------------	---------

APPENDIX D

Curves	314-321
------------------	---------

APPENDIX E

Extracts from A.S.M.E. Power Test Preliminary Report . . .	322-325
--	---------

INDEX	327-331
-----------------	---------

HEAT

CHAPTER I

ENERGY

THE utility of any bit of human knowledge, taken by itself, is not great. The full significance is not realized until we get a clear understanding of the relation of one fact to all others. Then only can we apply knowledge to maximum advantage.

While everyone knows much about "Heat," the relation that this information bears to other knowledge, which we classify under mechanics, electricity, and other applied subjects, is established more clearly in the mind by a process of systematization and correlation.

The most helpful topic under which to correlate the facts, principles and laws which are usually studied in applied physics is energy.

1. Energy. If we are scientifically exact, we find that there are many conceptions of elementary things, like electricity, matter and energy, which cannot be exactly defined. Yet energy is such a common and well-known thing that we all think we know, well enough for all practical purposes, what it is. For a rough-and-ready sort of definition we say that "Energy is what makes things go." This is naturally our first idea of energy, because we are made conscious of the existence of energy by active processes.

We must recognize that the energy exists all the while, even though it attracts no attention to itself. Thus in a shell loaded with powder we have a quantity of energy stored in the powder. When we explode the shell the energy is largely transferred to the bullet. When the bullet hits another body the energy is partly passed on. If we never heard about burning powder and being hit by bullets, we would know nothing about the energy in a cartridge. Though the cartridge is never exploded and we never suspect the energy within, clearly it exists there just the same. Accordingly a full investigation of energy should concern itself with energy when it is passive, as well as when an active transfer is taking place.

Sections 2 and 3 will be devoted to a discussion of "ENERGY OF MOTION," and "FIXED ENERGY" under which headings all forms of energy may be classified.

When the cartridge previously referred to is exploded, energy is transferred from the explosive to the projectile, and we say that work is done upon the projectile. In practically all cases where work is done a careful analysis of the process will show that energy has been transferred. This leads us to define work as the quantity of energy transferred.

If we make a quantitative study of energy, we use one of the *work units* given in Table II to express quantity of energy.

From our knowledge of mechanics we recall that work is done when a force is applied to a body and the body moves while the force is still acting. Thus, if a force of 1 lb. is exerted through a distance of 1 ft., 1 ft.-lb. of work is done. If the 1 lb. is applied through 2 ft., then 2 ft.-lbs. of work are done. Similarly, if a 2 lb. force presses against a body and it moves in the direction of pressure 1 ft., 2 ft.-lbs. of work will again be done. Work, therefore, is measured by the product of the two factors—force and distance,

$$\text{Work} = \text{force} \times \text{distance.}$$

Whenever we say that a body possesses energy, we mean that it is capable of doing work. If we use all

the energy to do work, and if we lose none in the process, the quantity of work done is, by our definition, an exact measure of the quantity of energy present. Thus, suppose we have a coiled spring, and we use it to lift a weight. If we find that the spring is able to do 50 ft.-lbs. of work, we say that it contains 50 ft.-lbs. of energy.

The converse of this proposition is also true. There can be no work done unless energy is taken from some body. The amount of energy so taken must be at least equal to the amount of work done.

2. Energy of Motion. All bodies, that are in motion, however large or small they may be, are said to possess energy of motion, or "KINETIC ENERGY." If a body, as the head of a hammer is in motion, it is capable of doing work because of that motion. The amount of work that this body is able to do is measured by the product of force the hammer can exert upon another body *times* the distance through which this force is exerted. A demonstration of the following may be found in any book on mechanics.

$$\text{Kinetic energy, or } KE, = FD = \frac{WV^2}{2g},$$

where F is the force, D is distance through which the force acts, W is the weight of moving body, V its velocity, and g is acceleration due to gravity in the same system of units as W .

Thus if we find that the hammer has driven a nail $\frac{1}{2}$ in. against an average resistance of 216 lbs., there was $\frac{1}{2} \times 1\frac{1}{2} \times 216$ or 9 ft.-lbs. of work done, and therefore 9 ft.-lbs. of energy were in the hammer. Or if it is determined that the velocity of the hammer just as it hits the nail is 24 ft./sec., and the weight of the hammer head is 1 lb., then the kinetic energy is

$$\frac{1 \times 24 \times 24}{2 \times 32} \text{ ft.-lbs.,}$$

which equals 9 ft.-lbs. again, and is a true measure of the work the hammer can do, and therefore of its energy.

Steam engines, motors, generators, water turbines, etc., furnish a fairly steady stream of energy of motion to machinery connected with them. The amount of energy furnished is always measured by determining the work done.

Other illustrations of energy of motion are discussed under "Electrical Energy," and "Light Energy." See Sections 7 and 8.

3. Fixed Energy. The continuous supply of energy of motion delivered by a steam engine is drawn from the coal, wood, or oil burned under a boiler. This coal is said to contain **FIXED ENERGY**, since the coal and its contained supply of energy may be kept indefinitely without appreciable loss.

Sometimes we speak of kinetic energy or energy of motion as being stored in a fly-wheel, but it will be noticed that this is but temporary, since the energy of motion of a fly-wheel or other piece of machinery soon leaks away if not put to prompt use. Clearly this is not fixed energy.

Coal is only one of a large number of substances which tend to oxidize or burn and in so doing free energy. In general, fixed energy is stored in all chemicals that are mutually eager to unite, or that, because of an unstable internal arrangement of the small particles that go to make up the mass, are eager to readjust themselves.

In mechanics, we have a kind of "fixed energy" which is often called "potential energy," or "energy of position." Thus, if a weight is raised to a height above the earth, it has energy due to its height, and if it is allowed to fall it will gradually transform its energy of position, or stored or fixed energy, into energy of motion or kinetic energy. This transformation will be complete at the instant when the weight hits the ground. We will see presently that when the

weight hits the ground the energy is not lost, but passes on to other bodies.

Other common illustrations of potential energy are: water elevated to a reservoir or tank, a coiled spring held by a detent, and any elastic body held out of its normal shape.

4. Forms Classified. In the table below are shown the forms that energy of motion and fixed energy take.

Energy of Motion.	Fixed Energy.
a. Mechanical energy	a. Mechanical energy
b. Electrical energy	b. Electrical energy
c. Light energy	
d. Heat energy	e. Chemical energy

5. Mechanical Energy. Energy possessed by a mass as a whole is called "mechanical energy." If the energy of a body is considered to be due to the motion of the body as a whole, the energy is said to be "kinetic energy in the mechanical form."

If the energy of a mass is due to its position, or if the energy contained in a mass is due to its elasticity, the energy is said to be "potential energy in the mechanical form."

These terms are doubtless thoroughly familiar, but, if a full discussion is desired, consult any mechanics text-book or encyclopedia.

6. Chemical Energy. Every chemical reaction that takes place is accompanied by the giving or taking of energy in quantities definitely proportioned to the weight of the chemicals involved. The case of the oxidation of coal, oil, wood, etc., has already been referred to. It is familiar because of the daily use of these substances to supply large quantities of energy. Most metals also are oxidized with an accompanying emission of heat. Zinc mill explosions have occurred due to the sudden oxidation of floating particles

of zinc in the air. It is very interesting to see a red-hot steel wire thrust into liquid oxygen at about -182° C. The burning of the steel liberates enough heat to warm up the oxygen from its very low temperature to that of white-hot steel and in addition to maintain the wire at a white heat in its cold bath.

No less interesting is the way chemical energy is stored and given off in various kinds of electrical batteries. In the type called primary batteries the chemical energy is transformed into electrical energy, and when the supply of energy is exhausted new chemicals are installed. In the so-called secondary batteries advantage is taken of the fact that the chemical reactions are reversible. When the supply of energy in a secondary battery has been nearly exhausted, electrical energy is sent *into* it, the chemical reaction is reversed, and a new supply of chemical energy stored up. The propriety of the name "storage battery" for the chemical secondary battery is apparent.

Chemical energy is fixed or *stored energy* due to the desire of one chemical substance to unite with another.

7. Electrical Energy. Wherever a quantity of electricity exists energy is present in the "electrical form." The electricity does work only when it is flowing, so we are mainly interested in electric current. The work done by an electric current is computed by finding the product of the current $\times$ pressure $\times$ time. The usual practical unit of work is the kilowatt-hour, which equals amperes $\times$ volts $\times$ time in hours divided by 1000.

The introduction of time into this computation is a frequent cause of misunderstanding of the true nature of work and energy. Amperes $\times$ volts is really a rate of doing work, since amperes is really rate of flow and is expressed by the rate: $\frac{\text{quantity}}{\text{time}}$. In the power unit then, we have $\frac{\text{quantity} \times \text{pressure}}{\text{time}}$, and to get our work in any practical case we must multiply by the time during which power

was being delivered at the rate indicated by the above expression, and we get

$$\frac{\text{quantity} \times \text{pressure} \times \text{time}}{\text{time}},$$

which equals quantity $\times$ pressure when the time has been canceled. Thus it will be seen that work and energy are measured electrically by taking the product of the quantity of flow times the pressure.

Commercially, electrical energy is transformed in large quantities by generators from mechanical energy delivered by either steam engines, water turbines, or explosion engines. This energy flows in streams through the electrical circuit just as kinetic energy flows in streams from the steam engine or through any machines connected to it. Therefore we class electrical energy as energy of motion, although there is one piece of apparatus, the condenser, in which it can be *fixed* for short intervals of time. For a full discussion of electrical energy, see any electrical text-book or encyclopedia.

8. Light Energy. There is a fairly well substantiated theory that all bodies are giving off a wave form of motion. Since no one has been able to find that these waves depend upon any form of matter for their propagation, it has been assumed that they are wave disturbances in an unknown medium called "luminiferous ether," which is supposed to uniformly pervade all space. When these ether waves are thrown from fairly hot bodies some of them affect the human eye and are called light waves, or rays of light. These rays of light that affect the eye are only part of the waves that are given off, as the eye recognizes waves only within a limited range of wave lengths. The longer wave lengths, however, we can feel when dense rays fall on our skin. These are the rays that we feel when we are at some distance from a hot stove or a bonfire. Such rays are called "heat rays." The shorter wave lengths usually come from extremely hot bodies and have

a strong disintegrating effect upon many substances. These are called "ultra-violet rays."

The only income of energy that the earth has is received in the form of these radiations from the sun and other heavenly bodies. But the earth is also giving off large quantities of energy in this form although the earth is so cool that the length of its waves is too great to affect our eyes and not so numerous as to affect our senses.

If we try to balance the earth's energy account, everything points to a continuous loss of energy by the earth.

The energy of the sun's rays is put to use in plants to build up from elements and extremely simple compounds the complex chemical compounds of which they consist.

Because of these well-known facts, "light" is an extremely familiar form of energy. As it has velocity of about 192,000 miles a second, it clearly must be classed as energy of motion.

9. Heat Energy: Its Nature. When light energy falls upon a body and is absorbed, we notice that the body becomes "warmer."

Now we know that there is energy in the light rays but apparently the wave motion is destroyed when the waves come in contact with the body; consequently the energy no longer exists as light energy. It would seem as if this giving up of energy has something to do with the body getting "warmer."

Again, if we send an electric current through this body, we shall find that it takes energy to do so and that the body is again made "warmer." Here electrical energy apparently warms the body.

Likewise, if we rotate a shaft in a bearing, we find that it takes energy to keep it rotating, and that the bearing tends to become "warmer." In this case we notice that just where our mechanical energy disappears we get certain effects, which we describe by saying that the body has become "warmer."

It would appear that in these cases energy in various forms has been used upon the body with the result that in each case the body has become "warmer."

Consider the case in which a mass is repeatedly struck with a hammer: The mechanical energy in the hammer is given up and no longer exists as mechanical energy of motion of the mass. Clearly it is either lost or is in the mass and in the hammer. If we place a thermojunction against the mass before striking it and if the mass is at the same temperature as the thermojunction, no electric current will flow through a connected galvanometer. If, however, the junction is taken away, the mass repeatedly struck with the hammer, and the junction again placed adjacent to the warmed mass, the junction will draw some warmth from the mass and we will notice a deflection of our galvanometer. We shall then have ELECTRICAL ENERGY in our circuit, which we have drawn from the mass, causing a loss of warmth. Since we have transformed mechanical energy into heat, and then transformed heat back into electrical energy, it would appear from this that heat is a form of energy since from the heat work was done.

Consider the case of a gasoline engine.

Air and gasoline are mixed in a carbureter and sucked into a cylinder in the gaseous form. By a spark or other means the gasoline is burned quickly, or as we say, exploded, and great heat is generated. This heat tends to expand the gas and produces a high pressure. The pressure forces the piston out and work is done. The energy now is in the mechanical form and the piston passes part of it on to some other machine or to the fly-wheel, where it may be temporarily stored.

While the engine goes through this series of operations, it takes in energy in the chemical form, and by first changing this energy into heat, delivers energy in the mechanical form. (See the definition of "engine," p. 37.) In this

example heat again seems to be a form of energy, for from the heat work was done.

If a weight is allowed to fall from a height and give up energy to a quantity of water by stirring it as is done in the apparatus shown in Fig. 1, after the water comes to rest it will be warmer. In other words, the mechanical energy of the weight has been transferred into heat energy of the water.

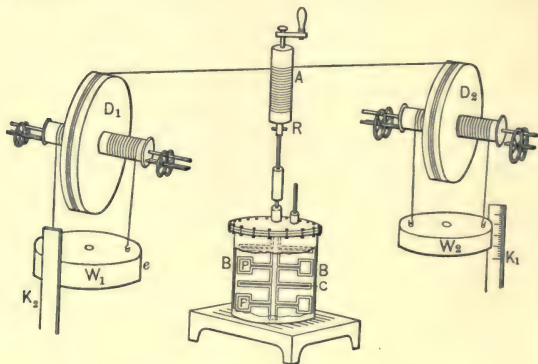


FIG. 1.—Joule's Mechanical Equivalent Apparatus.

The mechanical energy was derived from the motion of a mass. The heat energy is present without any motion of the mass of water, but seems to be internal.

The accepted conception of the nature of heat energy is the "**kinetic theory**," which, briefly stated, is that heat energy is due to the motion of the small particles—molecules—which go to make up a mass.

The prevailing scientific conception of matter is that a mass is made up of molecules. These molecules in turn are made up of atoms, of which there are about 81 kinds known. The atom is not now considered to be the smallest division of matter, but is supposed by

some scientists to be made up of a varying number of electrons plus a corpuscle. A notion of the relative size of a mass, molecule, and atom may be had by considering, first, a crystal mass of cane-sugar. This is made up of a large number of molecules, each in turn containing not less than 45 atoms of various kinds. In a similar way we have the universe, made up of solar systems, of which our sun and the bright stars are centers. These solar systems are made up of a sun and a number of planets. The ratio between the diameter of the solar system and the diameter of the universe we conceive as a very small fraction. Also the ratio between the diameter of the solar system and one of the planets is a very small fraction. Of the same order of magnitude as the first fraction is the concept of the ratio between the diameter of the mass and the diameter of a sugar molecule. Similarly, the ratio between the diameter of an atom and a molecule is thought of as in proportion to the ratio of the diameter of the earth and our solar system.

According to the kinetic theory, we must think of the molecules that go to make up a mass as in constant motion. The orbit of this motion is extremely small relatively to the whole mass, yet extremely large relatively to the diameter of the molecule. The orbit of this motion is restricted by occasional collisions which probably take place between only two molecules at a time as the molecules are so sparsely scattered in the mass.

The energy of the molecule due to its motion will be measured by the usual formula, $KE = \frac{WV^2}{2g}$. For a fixed weight of any given substance and consequently for each molecule, we find that the heat energy is approximately in proportion to its temperature. But since heat energy is due merely to the kinetic energy of the molecule, the mean velocity of the average molecule must vary as the square root of the temperature, or this velocity squared must vary as the temperature varies.

An interesting experiment is sometimes made to suggest the way the stored energy of a whole mass when it falls and acquires kinetic energy suddenly is transformed to heat energy when it strikes another body. Notice what happens when a drop of mercury falls from a

height. It first has potential energy due to its position, which is changed to kinetic energy just before it reaches the floor. When it strikes the floor the motion of the mass stops, but a large number of small globules of mercury scatter in every direction at a rapid rate. If instead of allowing the mercury to fall upon the floor, it be made to

fall into a closed vessel and if the temperature be determined before the mercury falls and again after it is collected in the vessel, the mercury will be found warmer after the experiment. Clearly, in this event, the potential energy of the mercury due to its position is changed to heat energy, and the energy has been transferred to the molecules.

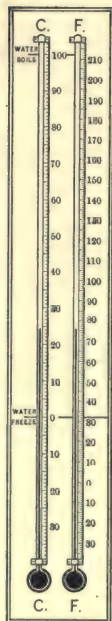


FIG. 2.

10. Temperature and Temperature Units. Whenever we increase the amount of heat energy stored in a body, as when we strike it with a hammer, we can feel an effect that we describe by saying that the body is *warmer*. When we take away heat we say that the body is cooler. Thus temperature is always *relative* to a previous condition, or relative to some fixed condition which we have in mind, and expresses how much warmer or cooler a body is relatively to a standard condition.

We use the words *hot* and *cold* to indicate direction in which energy may be expected to be transferred. Hot and cold do not indicate the state or temperature of a body.

As a standard to which to refer differences of temperature, the civilized world has agreed upon the freezing- and boiling-points of pure water under a pressure of 760 mm. of mercury. In order to express more definitely the amount hotter or colder, the difference in temperature between these two fixed points of reference has been divided into an arbitrary number of divisions called degrees. The number of degrees between

the freezing-point and the boiling-point of water in the English or Fahrenheit scale is 180; and in the French or Centigrade is 100.

In daily conversation people frequently express temperature by saying that it is so many degrees Fahrenheit or centigrade above freezing, which is the logical beginning of a temperature scale for daily use. In the centigrade system freezing is the zero point. About the year 1714, Fahrenheit, one of the first to undertake accurate temperature measurements, selected the lowest point that he could reach by artificial means as the zero of his scale, and the temperature of the human body as 100°. In the scientific evolution of his thermometer, the scale was slightly altered to use the freezing- and boiling-points of water as points of reference. When freezing was taken as 32°, and boiling 212°, blood heat turned out to be 98°. It thus happens that the thermometer most used by English-speaking people has a very illogical and awkward scale.

These facts about the various temperature scales are shown in the table below, and in the diagrams appended.

A further discussion of thermometers will be found in Chapter VII.

	Abbre- viation.	Freezing- point Number.	Boiling- point Number.	Difference between Fixed Points.
Centigrade	C.	0°	100°	100
Fahrenheit	F.	32°	212°	180

To change from one scale to another these facts should be kept in mind:

- (a) The difference in zero point;
 - (b) The difference in value of one degree on the scale.
- 100 centigrade degrees = 180 Fahrenheit degrees.

1 centigrade degree = $\frac{9}{5}$ Fahrenheit degree.

$\frac{5}{9}$ centigrade degree = 1 Fahrenheit degree.

To change a centigrade temperature to the corresponding Fahrenheit temperature, it is necessary to multiply by nine-fifths to find the number of degrees Fahrenheit above the freezing-point and then add 32° .

To change a Fahrenheit temperature to the corresponding centigrade temperature, it is first necessary to subtract 32° , and then multiply by five-ninths.

Problem 1. Change 95° F. to C.

95° F. is 63 Fahrenheit degrees above the freezing-point.

1 F. degree = $\frac{5}{9}$ of 1 C. degree, thus 63° F. = $63 \times \frac{5}{9}$ or 35 C. degrees.

35 C. degrees + 0 (value of freezing-point) = 35° C.

or 95° F. = 35° C.

Problem 2. Change 40° C. to F.

40° C. is 40 centigrade degrees above freezing-point.

1 C. degree = $\frac{9}{5}$ of 1 F. degree, thus 40 C. degrees = $40 \times \frac{9}{5}$ = 72 F. degrees.

72 F. degrees + 32° (value of freezing-point) = 104° F.

or 40° C. = 104° F.

Problem 3. Change 50° C. to F.

Problem 4. Change 240° F. to C.

Problem 5. Change -40° C. to F.

Problem 6. Change -20° F. to C.

Problem 7. If the temperature of your body is 98° F., what would it be in centigrade?

Problem 8. Zinc melts at approximately 415° C.; what is its melting-point on the Fahrenheit scale?

Problem 9. If oxygen boils at -297° F., what is its boiling-point on the centigrade scale?

Problem 10. If carbon dioxide boils at -79° C., what is its boiling-point on the Fahrenheit scale?

11. Units of Quantity of Heat Energy. It would naturally be expected from our previous discussion of energy that the logical unit by which to measure heat energy is a work unit. However, no convenient work unit is available, and we must use units which have in them as factors temperature and quantity of mass.

For experimental purposes the most convenient material for a standard mass is water, as it is easily obtainable in a chemically pure state, and has a very great heat capacity per unit of weight. Accordingly, in the metric system we have as our unit of heat quantity the calorie.

A **Calorie** IS THE AMOUNT OF HEAT ENERGY NECESSARY TO CAUSE ONE GRAM (1 c.c.) OF PURE WATER TO RISE 1° C.

The corresponding English unit is the British thermal unit.

A **British Thermal Unit** (B.T.U.) IS THE AMOUNT OF HEAT ENERGY NECESSARY TO CAUSE A POUND OF PURE WATER TO RISE 1° F.

1 B.T.U. = 252 calories.

Other units are useful at times when the B.T.U. or the calorie is too small or when using a thermometer system different from the weight system. Although not in common use for permanently recording experimental results, in computations and in taking data the following correctly represent a definite amount of heat energy, and may be used in exactly the same way as the calorie and the B.T.U.:

- 1 lb.-degree C.,
- 1 ton -degree C.,
- 1 ton -degree F.,
- 1 kgr.-degree F.,
- 1 kgr.-degree C, etc..

These units of quantity of heat energy should be carefully distinguished from units of temperature. Temperature alone tells us nothing about the quantity of heat energy in a body, but merely whether we may expect heat energy to be transmitted to or from other neighboring bodies whose temperature is also known. The quantity unit is a measure of the amount of energy so transmitted.

For work demanding accuracy exceeding one part in 500, the quantity unit should be more exactly defined. The inaccuracy arises

from the fact that the quantity of heat energy necessary to raise a given mass of water 1° is not constant. In fact, below the boiling-point there is a maximum variation of nearly one per cent. However, if experiments are always conducted with the water below 50° C., an error exceeding $\frac{1}{2}$ per cent is not probable.

There is a strong tendency to take as the more accurate definition of the calorie the energy necessary to heat 1 gr. from 19.5° C. to 20.5° C. and for the B.T.U. the energy to heat 1 lb. from 67° F. to 68° F. Some scientists urge the adoption of 14.5° C. to 15.5° C., others the quantity required to heat from 17° C. to 18° C., and many engineers the mean value between 0° C. and 100° C. The logical way to settle this discussion would be to define the calorie and B.T.U. in terms of the equivalent number of foot-pounds or other work units. This, however, is not practicable, because we cannot experimentally transform mechanical energy into heat energy with a greater accuracy than $\frac{1}{2}$ per cent.

12. Relation between Mechanical and Heat Units and Electrical and Heat Units. The units of quantity of heat do not mean much to us from a practical standpoint until we have determined their relation to the mechanical and the electrical units of energy. There is no simple mathematical way of finding the numerical relation. We have to depend upon experimental values.

J. P. Joule, an English business man, made a classical series of determinations of this quantity. The first of these was started about 1841 and the last in 1878. In Fig. 1, page 10, is shown the essential details of his apparatus. The weights W_1 , W_2 in falling rotate the small drum A and thereby make the paddles P stir the water in the calorimeter C . By withdrawing the pin R the weights may be again wound up without moving the paddles. By repeating this process he obtained measurable quantities of heat energy. This result was at first about one per cent lower than the value now in common use.

Professor H. C. Rowland, of Johns Hopkins University, Baltimore, undertook in 1879 to check Joule's work with more modern apparatus. He drove the paddles by a steam engine, used thermometers that were more accurately calibrated by comparison with standard instruments, corrected for the variation of the heat capacity of water at different temperatures, and in various other ways reduced the errors of the earlier work.

Osborne Reynolds and W. H. Moorby in 1897 made a determination, using a Prony brake with a water-cooled jacket. Their brake is shown in Fig. 3. They experienced great trouble from moisture in the insulation material used to protect the brake from loss. They used a 100 H.P. steam engine to supply their energy but while they worked with good-sized quantities their results could easily have contained an error of $\frac{1}{2}$ per cent.

Numerous other methods of determining the mechanical equivalent of heat by converting mechanical energy directly to heat energy have been tried with great care in the attempt to establish experimentally the relation between the mechanical energy units

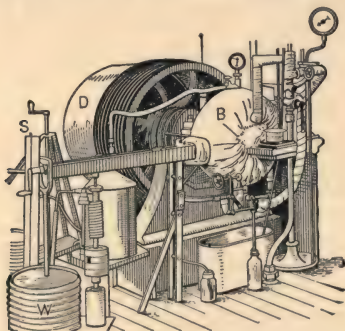


FIG. 3.—Reynolds and Moorby's Prony Brake.

and the heat energy units. However, none of these has proven so satisfactory as have experiments in which electrical energy is changed into heat energy. The mechanical equivalent of the electrical units has been defined and may be experimentally applied with an accuracy of a higher order than is obtainable in heat experiments. Then, if the relation of the electrical energy units and the heat energy units (i.e. the electrical equivalent of heat) is obtainable with an error of less than $\frac{1}{2}$ per cent, it gives us information as to the mechanical equivalent of heat.

Professors Hugh L. Callendar and H. T. Barnes, of McGill University, used a piece of apparatus illustrated in Fig. 4, which gave the greatest probable accuracy yet obtained. The apparatus was supplied with a continuous stream of electrical energy which was delivered in

the straight tube *AB* to a platinum wire resistance coil. This coil is bathed in a stream of liquid (usually water) flowing along this tube. As the liquid enters and leaves this tube, its temperature is taken by a set of delicate thermocouples, which are so connected to a galva-

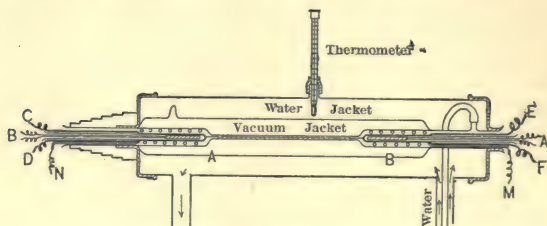


FIG. 4.—Electrical Equivalent Apparatus.

nometer that the galvanometer deflection is in proportion to the difference in temperature. By this arrangement, the apparatus may be operated under constant conditions for considerable periods of time and rates of flow of energy along the various possible paths obtained very accurately.

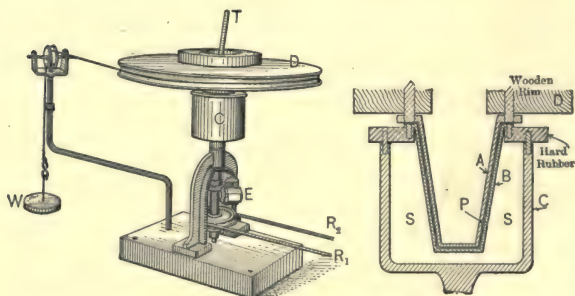


FIG. 5.—Mechanical Equivalent Apparatus.

The Searles apparatus shown in Fig. 5 is driven by a handwheel not shown in the cut. The rope R_1 , R_2 runs over the handwheel and causes the cup *C* to rotate. The meter *E* shows the number of

times that the cup *C* (and also *B*, which moves with it) is rotated. Cup *A* does not rotate, but is held back by a suitable weight *W*. This weight *W* is adjusted until it is just enough to balance the friction between cups *A* and *B*. *P* is a thin sheet of paper introduced between *A* and *B* to make the friction more uniform. To overcome the friction between these two thin brass cups *A* and *B*, mechanical energy is given to the apparatus. The amount of energy so furnished is obtained as follows: The work done against friction per revolution equals the weight in pounds *W* times the circumference of the pulley in feet *D*, since *W*=force and the circumference the distance through which the force was exerted, and force $\times$ distance = work.

In computing the work done, we consider that *D* has moved relatively to *C*, which we may consider as remaining in a fixed position.

The total work will equal the work per revolution times the number of revolutions or

$$W \times \text{diameter of } D \times \pi \times \text{revolutions turned through.}$$

This quantity is to be equated to the heat in B.T.U.'s gained in the cups. The heat gained *equals the rise in temperature* of the cups and contents, $\times$ the sum of the (weight of water in the cups and the water equivalent of the cups). (For a more complete discussion of the methods of calorimetry see p. 47.)

DATA AND CALCULATIONS

Weight of cups.....	=	.325 lb.
Weight of water.....	=	.0645 lb.
<i>W</i>	=	.545 lb.
Diameter of drum.....	=	14 ins.
Room temperature.....	=	75.2° F.
Initial temperature of water and cups.....	=	61.87° F.
Final temperature of water and cups.....	=	88.78° F.
Total revolutions.....	=	1020
Rise in temperature of cups, etc.....	=	26.91°
Water equivalent of cups and water in cups.	=	.0970 lb.
Total heat developed = .0970 $\times$ 26.91.....	=	2.61 B.T.U.

$$\text{Work done} = \frac{545 \times 22 \times 14 \times 1020}{7 \times 12} = 2038 \text{ ft.-lbs.}$$

$$2.61 \text{ B.T.U.} = 2038 \text{ ft.-lbs.}$$

$$1 \text{ B.T.U.} = 780 \text{ ft.-lbs.}$$

While this result is higher than the accepted value for the mechanical equivalent of heat, it is very satisfactory considering that there were no special precautions or corrections applied except to start

with water as far below the temperature of the room as it was raised above. One per cent variation is to be expected with this apparatus.

The resistance coil, shown in Fig. 6, is used to determine the electrical equivalent of heat. The wire is of a special alloy, "1a 1a," having a constant resistance at all ordinary temperatures. It is wound on a hard rubber frame *R*. The ends are connected to the two posts *A*, *B*.

The coil is placed in a small beaker of *distilled* water and a known current is sent through it for a time long enough to raise the temperature as far above that of the room as the initial temperature was below. The total electrical work done on the coil is written on one side of an equation and the total heat energy developed on the other side. The equation is then simplified and the answer appears in substantially one of the forms shown in Table II.

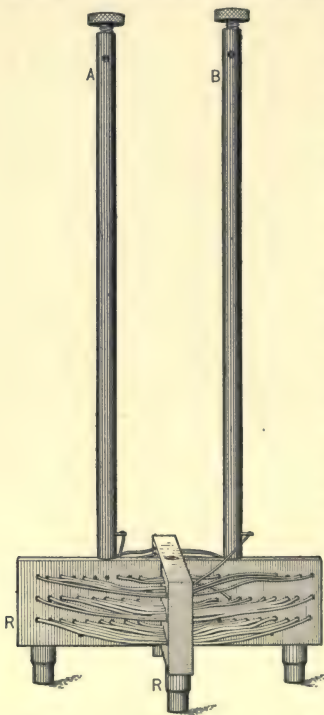


FIG. 6.—Immersion Resistance Coil.

Brown's apparatus for making this same determination is shown in Fig. 7. It consists of a thirty-two candle-power carbon filament bulb in a micanite weather-proof socket, into which is screwed a short piece of brass pipe joined at the upper end to a wooden head. This head carries a

pair of Fahnestock binding posts for the terminals of the lamp. All the joints about the lamp socket are sealed with beeswax to keep out moisture.

With the electrical connections shown in Fig. 7, two sets of data are taken, but only the set using the metal calorimeter *C* is necessary for determining the electrical equivalent of heat. This calorimeter is made of copper and has a metal cover as well, so that no energy is allowed to escape from the lamp in the form of light or other radiations.



FIG. 7.—Electrical Equivalent Apparatus

DATA AND CALCULATIONS

	METAL CAL.	GLASS CAL.
Weight of glass in lamp bulb.....	30 gm.	30 gm.
Temperature of room.....	19° C.	21° C.
Weight beaker, rod and cover.....	600 gm.	710 gm.
Weight beaker, rod, cover, and water..	2070 gm.	1250 gm.
Temperature at start.....	16° C.	17° C.
Highest temperature of water.....	23° C.	25° C.
Time at start.....	12 hr. 2' 0"	11 hr. 23' 30"
Time at finish.....	12 hr 9' 30"	11 hr. 28' 0"

	VOLTS.	AMP.	VOLTS.	AMP.
Electric measurements.....	105	.99	105	1.00
	104	.98	107	1.03
	106	1.00	104	.99
	103	.98	105	1.00
	107	1.01	105	1.00
	105	1.00		
	104	.98		
	105	.99		

	METAL CAL.	GLASS CAL.
Mean spherical c.p. from glass calorimeter.....	....	22.4
Weight water and water equivalent...	1525 gm.*	730 gm.
Rise in temperature.....	7.0 C.	8.0° C.
Calories of heat developed.....	10,670	5840
Time of run in seconds.....	450	270
Average volts.....	105	105
Average amperes.....	.99	1.00
Total watts delivered to lamp.....	104	105
Electrical energy used in watt-seconds.	46,800	28,400
Electrical equivalent in calories per watt-second.....	.236	(.206)
or in watt-seconds per calorie.....	4.21	(4.85)
Mechanical equivalent in foot-pounds per B.T.U.....	788	(690)

While this set of data and computations was carried to three significant figures, the third place represents only an estimated value, since the electrical readings were accurate to only one per cent. No correction for radiation, conduction, or convection was used, but the loss was probably too small to be significant, as the experiment was started with the calorimeter at a temperature as far below that of the room as it was carried above.

GLASS CALORIMETER

The second set of data gives some interesting information on the amount of energy that goes from the lamp in the form of ether radiations. The value of the electrical equivalent is seen to be smaller by about 12.7 per cent than the value obtained in the previous set of data. 12.7 per cent of 105 watts or 13.34 watts therefore were

* The water equivalent was found by trial to be 55 grams of water.

radiated from the lamp out through the glass calorimeter. All of these radiations were not visible but resulted in 22.4 mean spherical candle-power of visible effect or light. This represents a light flux of $22.4 \times 4\pi$ or 282 lumens. Then 1 watt will furnish $282 \div 13.34$ or 37.6 lumens along with some other radiations. While this is not in any accurate sense a value for the light equivalent of 1 watt of electrical power it gives a clue as to the rate of flow of light energy.

In conclusion it may be stated that by placing a suitable resistance in distilled water and sending current through it we find that 1 calorie of heat energy appears in the water for every 4.2 watt-seconds of electrical energy used up in the coil. It has also been found that by stirring water with a system of paddles, 1 B.T.U. of heat energy will be given to the water when 780 ft.-lbs. of work have been done upon it.

For the solution of the succeeding problems it is well to refer to the appendix for numerical relations existing between the various mechanical, electrical and heat units, and much time may be saved in computations if care is taken to select the most convenient constant. (See Table II.)

Problem 11. A coil of wire having a resistance of 20 ohms and carrying a current of 6 amps. is placed in a beaker containing 700 gms. of pure water. Neglecting the heat capacity of the beaker how much rise in temp. of the water would be produced in 49 seconds?

$$\text{Watts used} = 20 \times 6 \times 6 = 720$$

$$\text{Watt-seconds} = 720 \times 49 = 35300$$

$$\text{Calories developed} = \frac{35300}{4.2} = 8400$$

$$\text{Rise in temp. produced in 700 gms.} = \frac{8400}{700} = 12.0^\circ \text{ C.}$$

Problem 12. A saw used to cut marble takes 10 H.P. How much water must be supplied per min. at a temp. of 50° F. to keep the work and saw at 80° F. ?

$$\text{Work per min.} = 10 \times 33000 = 330000 \text{ ft.-lbs.}$$

$$\text{in equivalent heat units} = \frac{330000}{780} = 424 \text{ B.T.U.}$$

$$\text{Each lb. of water takes away} \quad 30 \text{ B.T.U.}$$

$$\text{Total water per min. required} = \frac{424}{30} = 14 \text{ lbs. 2 ozs.}$$

Problem 13. If a 60-watt lamp is placed in a vessel containing 1.93 k. grs. of water at 20°C. , how long will it take the water to come to the boiling-point if all the energy remains in the water?

Problem 14. If a Prony brake is found to be absorbing 8 H.P., and if cold water is run in continuously at 40°F. , and is spilled out at 150°F. , how much water per minute must be allowed to flow to prevent any increase in temperature of the brake?

Problem 15. Apparatus is arranged so that the energy from .5 k. grs. falling through 1.860 kilometers is used to stir 93 gms. of water whose original temp. was 15°C. What was the final temp.?

SUMMARY, CHAPTER I

ENERGY is a familiar idea that is not readily defined.

WORK is Quantity of Energy. When we talk quantitatively about energy we use work units. The process of doing work takes place when energy is transferred.

ENERGY Takes Various Forms, such as the mechanical, electrical, light, and heat forms. These we classify into Energy of Motion and Fixed or Stored Energy.

HEAT ENERGY is Energy of Motion. The motion is molecular and the total energy is in proportion to the velocity squared of the average molecule. The Total Heat Energy of a mass is the Total Kinetic Energy of the molecules.

TEMPERATURE Expresses how much Hotter or Colder a Body is than some other Body. Temperature is relative and tells which way we may expect heat energy to be transferred. The boiling- and freezing-points of water are the ordinary points of reference.

The **RELATION** between the various mechanical, electrical, and heat energy or work units must be found experimentally.

ONE DEGREE CENTIGRADE is $\frac{1}{100}$ of the difference in temperature between boiling and freezing of water.

ONE DEGREE FAHRENHEIT is $\frac{1}{180}$ of this same difference. The **ZERO** on the Fahrenheit scale is **32° Below Freezing**. This point should always be remembered in changing from one system to the other.

The **CALORIE** and the **B.T.U.**, are **Quantity Units** of heat energy and consequently are **work units**.

A **CALORIE** is the **Heat Energy Necessary to Raise 1 gm. of Water 1° C.**

A **B.T.U.** is the **Heat Energy Necessary to Raise 1 lb. of Water 1° F.**

CHAPTER II

ENERGY FROM FUELS

13. Fuels. Any substance that may be oxidized or burned and thereby made to produce heat energy in commercial quantities is called a fuel. Practically all fuels are made up of either pure carbon or of carbon and compounds of carbon formed with hydrogen, nitrogen, oxygen, sulphur, etc. Gaseous fuels have no free carbon, but may contain besides carbon compounds uncombined hydrogen, nitrogen, oxygen, etc. Liquid fuels may have various impurities in mechanical mixture with the carbon compounds. Solid fuels contain all of the above plus moisture, ash, and a great variety of elements and compounds in small quantities. The following definitions are in good usage to classify the constituents of coal.

Ash. Earthy matter and other impurities that remain as solid residues after burning is completed are classed as Ash. This subject has never been given the attention that it should receive. While commercial coal produces from 4 to 25 per cent of ash in the case of the coals having the high per cent no attempt has yet been made to carefully study the chemical changes and the energy relations in this part of the fuel. Probably on a good grade of coal there is no appreciable energy lost or gained due to chemical reaction in the ash. If the ash tends to "melt or fuse" and form clinker it is likely to clog the grate. Ash always interferes with the draft.

Moisture. In a fuel the uncombined water that may be driven off by continued heating for an hour at a temperature between 105° C. and 107° C. is classed as MOISTURE. Coal as mined always contains some water. This may be increased in shipment by rain or by turning on a hose. The water may also dry out to some extent along with certain volatile matter. The heat value of coal as weighed may be very much less per pound than a dried sample shows

when tested in a fuel calorimeter. Moisture in coal greatly reduces its value as a fuel because of the large quantity of energy required to drive off the moisture. This energy must be subtracted from that in the fuel to give its correct fuel value. The numerical relations involved will appear from problems to be solved later. See Chap. V, Problems 12, 13 and 18.

Volatile Matter. All of the constituents of coal that may be driven off in the form of gas before combustion takes place are classed as **VOLATILE MATTER**. From this quantity it is usual to exclude all water that may be dried out by an hour's heating at a temperature between 105° and 107° C. Included, however, there will always be some carbon dioxide, nitrogen, and other gases which do not change in chemical composition and consequently do not generate or absorb heat. The sample is brought to red heat in a closed crucible. If no oxygen is allowed to reach the sample no burning will take place.

Fixed Carbon. All the combustible mass remaining after the volatile matter is driven off is called **FIXED CARBON**. This is usually obtained by subtracting the ash from the total residue after the volatile matter is driven off.

An Ultimate Chemical Analysis, if at all complete, should show the percentage of carbon, hydrogen, nitrogen, oxygen, sulphur, and ash. Frequently the percentages of phosphorus, iron, pyrites, etc., are required before the suitability of a given fuel for a given purpose can be determined.

A Complete Chemical Analysis should give the compounds and elements in the per cent in which they exist in the sample as received.

A Proximate Analysis should show the moisture, fixed carbon, volatile matter, ash, and sulphur.

Classification of Solid Fuels into various grades and sizes of anthracite, bituminous coal, lignite, and peat is on a commercial rather than a scientific basis, and the reader's general experience will contribute an adequate understanding of the distinction between the various kinds.

Coke is the residue obtained by driving off the volatile matter from coal (usually some form of bituminous).

Charcoal is the residue obtained by driving off the volatile matter from wood. Both coke and charcoal contain all the ash, therefore, all the solid impurities of the original fuel.

Liquid Fuels. The various hydrocarbon compounds that go to make up mineral oil are the liquid fuels most commonly used. Much oil in the crude state and a constantly increasing amount of alcohols are used.

Since liquid fuels have to be vaporized before they are burned, they are really used as gaseous fuels, but are more conveniently handled as liquids.

Gaseous Fuels. In some localities natural gas is available but, in general, gas is made from coal or liquid fuels. A proximate chemical analysis of the type usual for coals and other solid fuels is valuable, but it does not indicate definitely the fuel value of a liquid or a gas. If the complete chemical analysis gives the per cent of the various compounds and elements in the fuel, a very accurate estimate of the fuel value can then be made. For illustration a purified producer gas would contain, nitrogen (N), oxygen (O_2), hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), and methane (CH_4). So-called "coal gas" will have in addition to the above: Ethylene (C_2H_4), illuminants, and occasionally water, hydrogen sulphide (H_2S), benzine (C_6H_6), etc. From an analysis giving the per cents of each, the fuel value may be computed by referring to Table III, for the fuel value of each of the constituent compounds and multiplying by the proper per cent.

Powdered Fuels. Fuels are frequently pulverized and blown with an air blast into furnaces used for metallurgical purposes. By this plan coals that clinker badly on a grate and that are low in heat value can be profitably burned. Coals high in volatile matter give especially good results when pulverized.

14. Air in Chemical Reactions. In the every-day use of fuels we support their combustion by supplying oxygen (O) from the air. Besides oxygen air contains nitrogen (N), which is an inactive gas and does not change its state or in any way enter into the chemical reactions. This *nitrogen* serves no useful purpose, but *dilutes the oxygen* and is extra matter that has to be moved and heated without any useful result. (See Chapter III, Section 25 and Problems 34 and 35.)

Air is about $\frac{1}{5}$ oxygen and $\frac{4}{5}$ nitrogen, but it also contains a variable amount of moisture, carbon dioxide (CO_2) and in small quantities hydrogen (H), helium (He), argon (A), etc. In ordinary computations of the amount of air required to burn a given amount of fuel, the composition of dry air may be taken as 20.7 per cent O, and 79.3 per cent N by volume, or 23 per cent O and 77 per cent N by weight.

As soon as CO_2 is formed, it is also considered as an inert gas like N, and no energy can be obtained from it.

Carbon monoxide is a *poisonous* gas. When heated to above 600° F. in the presence of oxygen it burns to CO_2 .

Below this temperature it acts as an inert gas like CO_2 and N.

The minimum proportion in which elements combine is given in tables of "Atomic Weights."

The common elements found in fuels with their atomic weights are:

Hydrogen	(H).....	1.008
Oxygen	(O).....	16.00
Carbon	(C).....	12.00
Sulphur	(S).....	32.06
Phosphorus	(P).....	31.00

Hydrogen burns with oxygen to water (H_2O), 2.016 gms. of H unite with 16 grams of O and 18.016 gms. of H_2O result.

12 gms. of C unite with 16 gms. of O to produce 28 gms. of CO; 12 gms. of C unite with 32 gms. of O to produce 44 gms. of CO_2 . When burning a fuel with a hot fire and with a plentiful supply of oxygen no CO is formed, but only CO_2 . If there is a scant supply of oxygen, conditions are more favorable for the formation of CO.

15. Energy Involved in All Chemical Reactions. Table III in the back of the book gives the energy developed by oxidization of carbon and some of its compounds that are commonly found in fuels.

It is a very important fact that, associated with the formation of not only products of burning, such as carbon dioxide, carbon monoxide, water, etc., but also with the formation of every other chemical compound, there is also a giving or taking of energy. This fact may be stated even more generally by saying that with every chemical change there is a giving or taking of energy.

A compound which absorbs heat energy during formation is said to be "endothermic." A compound which gives up heat energy during formation is called "exothermic." This text deals mainly with

the heat energy transformed, but there may be electrical energy transformed as well.

From the above statement it follows that the amount of energy which a compound will give up when oxidized or burned depends somewhat upon how much was taken on or given off when the compound was formed.

For example, acetylene has the chemical formula C_2H_2 and benzine C_6H_6 . Now one would expect equal weights of these two compounds to develop equal quantities of heat energy, but 1 lb. of acetylene, which is an endothermic compound, gives as much energy as 1.18 lbs. of benzine. For exact values see Table IV.

16. Heat Energy of Fuels. All our most accurate knowledge of the energy changes that go with chemical changes are derived from experiments. The methods of determining the energy liberated from fuels are discussed in Chapter VII, together with the descriptions of the various calorimeters, etc., used.

The heat energy relations associated with the oxidation of chemical elements and the more common organic compounds have been carefully determined, and a few of these are to be found in Table IV. These determinations enable us to compute the fuel value of liquids and gases when we have a complete chemical analysis and, from an approximate analysis giving the per cent of elements, we can make a rough estimate of the energy available in coals. These computations are very important in flue gas tests, gas generator tests, furnace tests, etc.

The following formulæ give a close approximation of the energy available in coals and are based on ultimate analysis, including moisture. In using these formulæ substitute the decimal part of a gram or pound of each element in place of the symbols C, O, H, and S. See Page 324.

$$\text{Calories per gm.} = 8110C + 34400\left(H - \frac{O}{8}\right) + 2200S,$$

$$\text{B.T.U. per lb.} = 14600C + 62000\left(H - \frac{O}{8}\right) + 4000S.$$

The last factor is frequently neglected, as the greater part of sulphur remains in the ash when combustion takes place on a grate.

The following problems will illustrate the use of these formulæ and the tables.

Problem 1. How many B.T.U. should sample No. 1 in Table IV develop? (See Page 298.)

Substituting in our formula we have:

$$\begin{aligned}\text{B.T.U.} &= \left[14600(70.73) + 62000 \left(4.87 - \frac{8.67}{8} \right) + 4000 \times .94 \right] \div 100 \\ &= 12710.\end{aligned}$$

Problem 2. Compute the calories per gram developed from sample No. 2 in Table IV.

$$\begin{aligned}\text{Cal.} &= \left[8110(68.69) + 34400 \left(4.84 - \frac{11.49}{8} \right) + 2200 \times 1.01 \right] \div 100 \\ &= 6860\end{aligned}$$

Problem 3. From Gas Analysis No. 1, Table V, compute the B.T.U. per cubic foot of this sample of producer gas: The heat developed by the combustion of each constituent gas of which the cubic foot is made up may be computed by multiplying the volume of each constituent by its heat of combustion as given in Table III. The sum of the separate quantities of heat developed by each constituent gas will equal the total heat of the cubic foot sample.

$$\begin{aligned}\text{B.T.U.} &= 338(\text{CO}) + 348(\text{H}_2) + 1052(\text{CH}_4) \\ &= 338 \times .112 + 348 \times .06 + 1052 \times .089 \\ &= 37.8 + 20.9 + 93.6 \\ &= 152.3 \text{ per cu. ft.}\end{aligned}$$

Problem 4. Suppose the coal in Problem 1 is burned in a furnace under a boiler and the fire-box ashes analyzed with the following result: Carbon 18.8 per cent, ash 81.2 per cent. Find the energy lost in the ashes per pound of coal used.

The pounds of coal per pound of fire-box ashes will be obtained by dividing the per cent of true ash in the ash from the fire-box by the per cent of ash in the coal, or $81.2 \div 13.41 = 6.06$ lbs.

Carbon wasted per pound of coal = $18.8\% \div 6.06 = 3.10\%$.

Energy wasted per pound of coal = $14540 \times .031 = 453$ B.T.U.

Problem 5. 9.17 lbs. of air were used to burn each pound of coal in Problem 1, and if the following analysis by weight of the flue gases resulted, find the heat energy in the stored or chemical form lost up the stack in the combustible gases:

$$\text{CO} = 1.0\%$$

$$\text{CO}_2 = 22.1$$

$$\text{CH}_4 = .2$$

$$\text{H}_2\text{O} = 4.4$$

$$\text{O} = 2.4$$

$$\text{N} = 69.9$$

$$\hline 100.0 \%$$

In 10 lbs. of gaseous products of combustion for 1 lb. of coal, we have,

$$.10 \text{ lb. CO} \times 4340 = 434.0 \text{ B.T.U. lost in CO}_2,$$

$$.02 \text{ lb. CH}_4 \times 23560 = 471.2 \text{ B.T.U. lost in CH}_4$$

$$\text{Total,} \qquad \qquad \qquad 905.2 \text{ B.T.U. lost up stack.}$$

Problem 6. Find the heat value of the coal in Table IV, Sample 3, in B.T.U. per pound.

Problem 7. In Problem 6 substitute in the formula for the calories per gram and give the relation that exists between the calories and B.T.U.

Problem 8. From the gas analysis of Sample No. 2, Table V, find the calories per liter developed upon oxidation.

Problem 9. From the analysis of No. 3 in Table V, find the B.T.U. per cubic foot developed during burning.

17. Explosives. An explosion consists of one or more sudden changes in pressure. An explosive is that which produces the explosion. High pressures which characterize most explosions are usually due to a *very rapid* burning of a fuel in a confined space. The essential conditions for such an explosion are: First, an intimate proximity of the necessary quantities of oxygen and combustible; second, the formation of gaseous products of combustion, and third, the transformation of chemical energy into heat energy in large enough quantities to heat the gaseous products of combustion to a high temperature.

Cotton we do not think highly of as a fuel. Under normal conditions it burns slowly with a great quantity of smoke. However, if cotton is soaked with liquid air, or better, liquid oxygen, and ignited, it may burn as quickly as gunpowder and with as little smoke. Thus an explosion is largely a question of having an intimate mixture of oxygen and combustible.

A common type of combustible entering into explosions is the gas given off from solid or liquid fuels and the pure gaseous fuels, like water gas, natural gas, producer gas, etc. None of these will explode until mixed with oxygen. People who like to do spectacular things frequently throw lighted matches into liquid fuels. This produces no disastrous results if there is no explosive mixture of gases above the liquid. The pure fuel will extinguish the match, because the match itself must have oxygen to burn. In most cases:

An explosive is an intimate mixture of oxygen and a fuel.

The explosion engines of to-day all use a mixture of air and a gas made from some fuel. The successful running of the engine demands that at the time that the explosion is started the gaseous fuel be thoroughly mixed with air in a suitable proportion. A detailed discussion of how this is arranged belongs properly in the chapter on gas engines and will be further discussed there.

The effect of the explosions may be greatly reduced by mixing with the explosives an inert gas like nitrogen, carbon dioxide, or steam. Thus in the gas engines it is necessary to sweep out of the cylinder all products of previous explosions, else they will dilute the incoming charge and also tend to cushion the explosion.

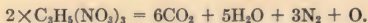
The explosion is more effective when the explosive is heated to a high temperature before explosion takes place. There are two reasons for this: First, because the total amount of heat energy after the explosion is greater, and, second, because the time necessary for the chemical reaction to be completed and for the energy to be transformed is shortened by increasing the temperature. The *violence of an explosion* is both a matter of the *amount of heat energy* released and the *time* required to completely transform this from fixed chemical energy to heat energy.

Explosives for use in firearms, mines, quarry work, etc., are divided into two classes:

Explosive mixtures,
Explosive compounds.

Explosive mixtures like gunpowder have separate compounds, one of which contains oxygen mixed physically. In gunpowder we may have 70 or 80 per cent of charcoal mixed with some sulphur and 10 or 12 per cent of potassium nitrate. The nitrate contains oxygen which when the mixture is heated is given off to combine with the charcoal and form CO_2 , K_2CO_3 , CO , N , and various other compounds are also formed.

In the explosive compounds, such as nitroglycerine and nitrocellulose, all the necessary material for burning is within each molecule. Nitroglycerine has the chemical formula, $\text{C}_3\text{H}_5(\text{NO}_3)_3$, and two molecules of it break up in accordance with the equation,



In this case fifteen gaseous molecules result from two liquid molecules, and since they are at first formed in the space occupied by the two liquid molecules, they are under great pressure. This pressure is increased by the large amount of heat energy transformed during the chemical reaction.

The effectiveness of these compounds, however, lies chiefly in the fact that, since the rearrangement is largely between atoms inside one molecule, the process is completed in an extremely short space of time. The disruptive effect increases greatly with a decrease of time. This fact leads to a classification of explosive compounds as high explosives and fulminates in contrast to the slow-burning gunpowders and other physical mixtures.

18. Exceptional Fuels. Various metals such as magnesium, iron, zinc, etc., can be burned. This property, in the case of magnesium, is much taken advantage of to make **Flashlights**, which are mild explosives, giving a light strong in the ultraviolet rays. No more spectacular application of knowledge of chemical and energy relations has been made than the application of **Thermite** to emergency repair and difficult welding. Thermite is both the fuel and the solder. Oxides of iron, magnesium, chromium, and other metals, and aluminium powder are mixed and placed in contact with the parts to be welded. When ignition takes place the aluminium takes the oxygen away from the other metals with evolution of great heat. This heat melts the iron or steel surfaces against which it rests and the metals in the thermite join the iron of the broken piece. The aluminium oxide tends to float to the surface and leave a solid metal joint. In this compound we have an explosive mixture which produces mainly a *solid* product of combustion and consequently there is not such a pronounced tendency toward expansion. The amount of heat

given off for any given percentage of aluminium powder and oxides may be computed from Table III.

19. Purchasing Coal. In purchasing coal it is clear that, other things being equal, what we want to get is the maximum amount of energy for the money expended. However, there are always other considerations besides the energy contained. Some coals tend to form clinker and cause trouble and extra labor in firing. If the coal contains considerable quantities of sulphur it may form corrosive compounds. Soft coal burns more freely than hard coal and there is frequently a great deal of choice between varieties when boilers are to be forced, because of firing qualities. In any particular furnace some types of coal will be found to work better than others, and so the choice is sometimes limited to a great extent by the conditions imposed.

Any fuel may be burned successfully in a properly designed furnace if the following conditions are fully met:

1. Fuel must be supplied uniformly over the grate surface and as nearly continuously as possible.

2. An air supply must be provided somewhat in excess of the amount theoretically required. This should not all be forced through the fuel bed in the case of fuels giving off large quantities of volatile matter.

3. A temperature above the fuel bed sufficiently high to ignite the gases driven off from fuel is required.

4. Before these gases reach any cooling surface such as the shell or tubes of a boiler they must be mixed with air and complete combustion must take place.

In anthracite coal usually 90 per cent of the combustible constituents is fixed carbon. It follows that the fuel value is mainly affected by the percentage of moisture and ash. As anthracite coal furnished for household purposes frequently contains as high as 25 per cent ash and 10 per cent moisture when delivered, it is readily seen that the purchasers

may effect considerable savings by giving these matters attention.

20. Heat Engine. A heat engine is any machine which *transforms* heat energy into mechanical energy. In common use we have but two varieties, the steam engine and the explosion engine, although the hot-air engine is sometimes used.*

The steam engine receives into its cylinder under pressure a hot gas which has a quantity of heat energy in it due to its temperature and its pressure. From this charge of hot gas the steam engine takes and transforms a small part of the energy into the mechanical form.

The internal combustion engine receives a charge of cold combustible gas and air which is burned in the cylinder, forming very hot gases as products of the burning. The chemical energy of the gaseous fuel is converted in the cylinder to heat energy and from this supply of heat energy work is done by the engine. The theory is essentially the same for all such engines whether they explode alcohol, gasolene, kerosene, crude oil, natural gas, coal gas, or producer gas. Practically there is great difference in the design and construction of these engines using the various fuels, due to the peculiarities of each fuel.

21. Power Plant. Any combination of apparatus that *transforms energy* from a *fixed* or *stored form* or from an *unavailable kinetic form* into *available energy of motion* is a power plant.

For example, a steam power plant transforms the energy of some fuel into mechanical energy by first giving the energy to water, which in gaseous form conveys the energy to an engine. The engine completes the transformation.

An hydro-electric power plant transforms the potential and kinetic energy of water into mechanical energy and the

*The "naphtha launch" really has a variety of steam engine.

dynamos transform the mechanical energy into electrical energy.

22. Efficiency = $\frac{\text{Output}}{\text{Input}}$. This is the familiar brief form

of the definition of efficiency. The following is a more complete statement:

The efficiency of a system or machine is the simultaneous ratio between the energy given out and that taken in. Input and output may be expressed either in work units (determined for a fixed time) or in power units. Preferably the same unit should be used in numerator and denominator when the efficiency should be stated in per cent. While this is the clearest and most logical way of expressing the result, commercially efficiency is frequently expressed by using a mixture of units. Thus the efficiency of a power plant is often given in pounds of coal per horse-power hour of output.

One pound of a given coal represents nearly as definite a quantity of energy as one horse-power hour. If the B.T.U. per pound of coal is known, the result obtained in horse-power hours per pound of coal can easily be computed to a per cent basis. This is done in Problem 1 below. In a similar way boiler efficiency is commonly expressed in pounds of water evaporated from and at 212° F. per pound of coal burned. This again can be reduced to a per cent basis when the energy in the coal is known. See Chapter VI for a discussion of problems of this character.

In technical literature there is only one common instance of the use of efficiency in any sense other than that given above. In the field of illumination, "efficiency" of electric lamps is stated as watts (a power unit) per candle power (a unit of intensity or intrinsic brilliancy of a light source). This gives a high value for a poor lamp and a low value for a good lamp, reversing the ordinary usage of the word.

Problem 10. A producer gas power plant burns 1.21 lbs. of coal testing 13,200 B.T.U. per pound for each horse-power hour delivered by the engine. Find the efficiency of the plant in per cent.

Reducing both to foot-pounds of work we have

$$\text{Output} = 1 \text{ H.P. hour} = 33000 \times 60$$

$$\text{Input} = 1.21 \times 13200 \times 780$$

$$\text{Efficiency} = \frac{33000 \times 60}{1.21 \times 13200 \times 780} = 15.9\%.$$

Problem 11. A steam power plant has an efficiency of 8.2 per cent and delivers each 24 hours 12,400 H.P. hours of work. Find the amount of coal, analyzing 13,800 B.T.U. that will be used per day.

Energy given out per day equals

$$(12400 \times 33000 \times 60) \text{ ft.-lbs.}$$

If x = the pounds of coal per day the energy used per day will be

$$(13800 \times 780 \times x) \text{ ft.-lbs.,}$$

$$\text{Efficiency} = \frac{12400 \times 33000 \times 60}{13800 \times 780 \times x} = .082,$$

$$x = \frac{12400 \times 33000 \times 60}{13800 \times 780 \times .082} = 27900 \text{ lbs. of coal per day.}$$

Problem 12. What is the efficiency of the engine in problem 10 if 40% of the energy in the coal is lost before the producer gas is delivered to the engine?

Problem 13. A steam electric power plant transforms 1 k.w. hour of energy from 1.12 lbs. of coal containing 14300 B.T.U. per lb. Find the efficiency in per cent.

Problem 14. How many horse-power hours should an explosion engine having an efficiency of 22 per cent develop per gallon of gasoline?

Problem 15. How many hours will a 60 H.P. gasoline engine of 22 per cent efficiency run on 10 gals. of gasoline?

Problem 16. How much ethyl alcohol per horse-power hour is required in an engine of 20 per cent efficiency?

REVIEW PROBLEMS, CHAPTER II

17. How many foot-pounds of energy would it take to do the work in above problem?

18. How many calories would it take to raise 1800 grams of water from 0°C. to 82°C. ?

19. A certain heat engine has an efficiency of 11 per cent. In burning 5 lbs. of coal, how much work can it do? (1 lb. of coal gives out 14,000 B.T.U.'s.)

20. If engine in Problem 19 burns the 5 lbs. of coal in 1 hour what horse-power is developed?

21. A locomotive while burning 120 lbs. of coal is able to draw a 400-ton train 2 miles up a grade of 20 ft. to the mile. Assuming friction as 10 lbs. to the ton, what is the efficiency of the locomotive?

22. If it takes 10 minutes to go the 2 miles in the above example, what must the horse-power of locomotive be?

23. The flow of water from tailrace of a mill is 1000 cu.ft. per minute. If the head of water is 12 ft., what horse-power will a water-wheel have which utilizes 6 per cent of the energy supplied by the water?

24. How many pounds of coal would a heat engine require per hour to generate the above horse-power, assuming an efficiency of 20 per cent?

25. An incandescent lamp uses 50 watts of electricity, 88 per cent of which is given off in heat. How many calories of heat are thus given off in one hour?

26. An engine is able to do 70 million foot-pounds of work by burning 112 lbs. of coal. How many pounds of coal does it consume per horse-power hour?

27. How many B.T.U.'s are required to raise the temperature of 195 lbs. of water from 32°F. to 212°F. ?

28. How many foot-pounds of work in 1 lb. of coal containing 12,000 B.T.U.?

29. How many horse-power hours of work are in 1 ton of coal containing 12,500 B.T.U. per pound?

30. How many kilowatt hours in 1 ton of coal containing 13,200 B.T.U. per pound?

31. How many pounds of water must be held at a height of 100 ft. to store an amount of energy equal to that contained in 1 lb. of coal yielding 13,800 B.T.U.?

32. If it takes approximately 400 B.T.U. per hour to keep up the natural processes in our body and if as a power plant we have an efficiency of 25 per cent, how many B.T.U.'s. per day must be taken into our body to keep the plant itself running?

33. Assume that a man, to whom the conditions in the previous problem apply, delivers, while operating a bicycle, .24 H.P. for 5 hrs. to the machine. How much energy per day (measured in B.T.U.) must he take in if the total energy in his body remains unchanged at the end of each day?

Assume the .24 H.P. to be used outside the body.

34. A power plant has 12 per cent efficiency and when run at its maximum capacity delivers 1800 kw. Find its coal consumption per day.

35. A steam plant uses 1.5 lbs. of coal per horse-power hour. Find the theoretical plant efficiency if each pound of coal contains 13,600 B.T.U.

36. A power plant has a coal consumption when run at full capacity of 25 tons per day. If its efficiency is 10 per cent, how many horse-power does it develop?

37. Assuming an efficiency of 5 per cent, how far up a grade of 24 ft. to the mile will 300 lbs. of coal take a train weighing 400 tons? Friction = 10 lbs. per ton.

38. If distance in Problem 22 is covered in one-half hour, what average horse-power is developed by the engine?

39. How many pounds of coal does the engine in Problem 22 burn per horse-power hour?

40. How far will a pound of coal containing 13,200 B.T.U. propel a train and locomotive weighing 400 tons against a rolling friction of 8 lbs. per ton, if all the heat energy is used to do work?

41. If the average plant efficiency of an Edison electric illuminating company is 12 per cent, and if they pay \$3 per long ton for a coal which contains 12,400 B.T.U. per pound, what does it cost the company for fuel per kilowatt hour "generated"?

42. If mechanical energy is being transformed into heat energy at the rate of 12 H.P., how many B.T.U. per hour will result?

43. 24 H.P. equals how many calories per minute?

44. 10 kw. equals how many calories per second?

45. Various experimenters have determined the amount of energy received by the earth from the sun, and it is fairly well established that outside the earth's atmosphere between 3 calories

and 3.5 calories are received per minute per square centimeter of surface normal to the sun's rays. If 2.5 calories per minute per square centimeter reach the earth, how many B.T.U. per square foot per minute does this represent?

46. If 11 B.T.U. per square foot per minute are received, how many square feet of area would apparatus receiving 10 H.P. require?

47. Apparatus exposing 1000 sq.ft. of surface receives on the average during a ten-hour day, 5 B.T.U. per square foot per minute. If the apparatus transforms the energy received into mechanical energy with an efficiency of 2 per cent, what average horse-power is developed during the 10 hours?

48. If a city lot 20×100 ft. receives energy at the average rate of 4 B.T.U. per square foot per minute for 10 hours per day and 25 days per month, how many tons of coal per month, each pound containing 12,000 B.T.U., would supply an equal amount of energy?

49. If the apparatus in the previous problem were used to transform the energy into mechanical energy and operated with an efficiency of 4 per cent, how many horse-power would be developed?

50. Consider the total area of the earth receiving energy to equal $(5280)^2 \times (4000)^2 \times 3.14$ sq.ft., and the population of the earth to equal 10,000,000,000. How many horse-power per human being are received if 3.5 calories per minute per square centimeter be taken as the rate?

SUMMARY, CHAPTER II

FUELS are substances which **burn and give off** stored or fixed energy in the form of **heat energy**.

A PROXIMATE ANALYSIS shows the per cent of moisture, fixed carbon, volatile matter, ash, and sulphur in a fuel.

AN ULTIMATE ANALYSIS shows the percentage of each of the elements in a fuel.

FUELS require **oxygen** from the air to burn and the products contain amounts by weight of their elementary (atomic) constituents in proportion to atomic weights of the elements combined.

EVERY CHEMICAL REACTION that takes place is accompanied by a taking of energy in the heat form (and sometimes in the electrical form as well).

PURCHASING COAL is a matter of **buying** an amount of fixed **energy** in the chemical form and not a weight or mass of material. Care must be used to see that the coal is adapted to the furnace in which it is to be burned.

A HEAT ENGINE transforms heat energy into mechanical energy.

A POWER PLANT transforms the fixed or stored energy of fuel or the mechanical energy of the wind, tide, or river, or the heat energy of the sun **into available mechanical energy** of motion or **electrical energy**.

EFFICIENCY = $\frac{\text{OUTPUT}}{\text{INPUT}}$. The output and the input are always taken at the same time; hence time is not a factor in defining efficiency. **A machine or a plant efficiency** is a ratio between the work given out and the work taken in.

CHAPTER III

SPECIFIC HEAT AND CALORIMETRY

23. Specific Heat. One B.T.U., if applied to a pound of lead at room temperature will cause a rise in temperature of about 33° F.; if applied to a pound of aluminum, 4.7° F.; if applied to a pound of water, 1° F.; and if applied to a pound of ice, originally at 0° F., one B.T.U. will warm the ice to approximately 2° F. It appears, then, that equal quantities of heat energy added to a unit mass of various substances do not produce an equal rise in temperature. The heat energy seems to **fill up** some substances faster than others, and so we think of each element and compound as having its own distinct "heat capacity."

It is customary to take the heat capacity of water as the standard, and compare other substances with it. The heat capacity or *specific heat* of a substance is the ratio between the amount of heat energy required to raise the temperature of a mass of the substance one degree and the amount of heat energy necessary to raise an equal mass of water one degree.

Using English units and for convenience taking 1 lb. of a substance:

$$\text{Sp.H.} = \frac{\text{B.T.U. of heat energy to raise 1 lb. of substance } 1^{\circ} \text{ F.}}{\text{B.T.U. of heat energy to raise 1 lb. of water } 1^{\circ} \text{ F.}}$$

But the heat energy to raise 1 lb. of water 1° F. = 1 B.T.U. Therefore, numerically, Sp.H. = B.T.U. of heat energy to raise 1 lb. of the substance 1° F.

Similarly, using metric units:

$$\text{Sp.H.} = \frac{\text{Calories of heat energy to raise 1 gm. of substance } 1^{\circ}\text{C.}}{\text{Calories of heat energy to raise 1 gm. of water } 1^{\circ}\text{C.}}$$

But the heat energy to raise 1 gm. of water $1^{\circ}\text{C.} = 1$ calorie.
Therefore, numerically, $\text{Sp.H.} = \text{calories to raise 1 gm. of substance } 1^{\circ}\text{C.}$

Accordingly, the following is true numerically:

Specific heat = heat energy to raise unit weight 1° .

Problem 1. A cast-iron bearing weighs 20 kgms. How many calories will heat it from 12°C. to 200°C. ? How many watt hours? (Assume no energy lost.)

Specific heat of the iron = .12;

Calories per degree. . . . = $20000 \times .12 = 2400$

Calories for 188° = $2400 \times 188 = 450000$ calories

Watt seconds = 450000×4.2

Watt hours = $\frac{450000 \times 4.2}{60 \times 60} = 530.$

Problem 2. How many heat units are required to raise the temperature of 300 lbs. of lead from 32°F. to 56°F. ?

Specific heat of lead = .031.

It requires .031 B.T.U. to raise 1 lb. 1° .

Therefore it requires $300 \times .031 = 9.3$ B.T.U. to raise 300 lbs. 1° .

It requires $9.3 \times (56 - 32) = 9.3 \times 24 = 223$ B.T.U. to raise 300 lbs. 24° or from 32°F. to 56°F.

Problem 3. How many foot-pounds of work would be necessary to produce the temperature change on the 300 lbs. of lead in Problem 2?

1 B.T.U. = 778 ft.-lbs.,

$223 \text{ B.T.U.} = 223 \times 778 = 173,000 \text{ ft.-lbs.}$

Problem 4. How many calories to raise 4 lbs. of aluminium from 0°C. to 328°F. ? (Specific heat of aluminium = .212.)

Problem 5. How many B.T.U. are required to raise the temperature of one ton of water from 40°F. to water at 382°F. ?

Problem 6. How many foot-pounds of mechanical energy would it take to do the work in the above problem?

Problem 7. How many calories will raise 20 lbs. of air from 10°C. to 25°C. under standard conditions of pressure?

Problem 8. How many B.T.U. are required to heat 12 lbs. of air from 60°F. to the temperature of a furnace fuel bed known to be at 2300°F. ? Assume the specific heat of air to average .240 for this range of temperature.

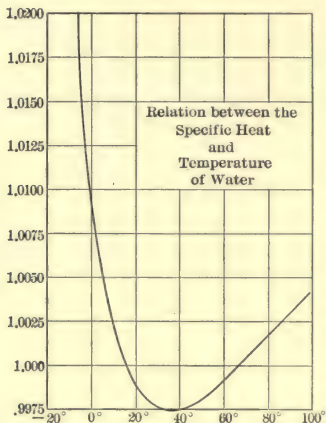


FIG. 8.

the air returned 43°F. ? Assume the air to have an average density of .0685 lb. per cubic foot and the entire volume of air displaced once per hour.

Problem 12. How many people, each giving off 400 B.T.U. per hour, must sit in this auditorium if the temperature does not change?

Problem 9. How much energy would be required to heat 1 lb. of coal from 60°F. to 2200°F. , if the specific heat of the coal over this range equals .22?

Problem 10. A cast-iron fly-wheel is fitted with a Prony brake equipped with cast-iron shoes. If wheel and shoes weigh 100 lbs. and 8.3 H.P. is being absorbed, how much rise in temperature in 5 minutes if no heat were lost?

Problem 11. How many B.T.U. per hour will it be necessary to extract from the air to cool an auditorium $132 \times 70 \times 28$, when the average temperature of the air drawn out is 85°F. and

Specific Heat is Not a Constant. The specific heat of any element or substance is not a constant, but changes when the temperature rises, and when a change of state, crystalline structure or density takes place. An examination of the table of specific heats in the back of

the book will illustrate these points. Notice particularly carbon and water. Fig. 8 shows the variation in the specific heat of water between the freezing- and boiling-points.

Specific heat is a ratio whose value is independent of the size of the unit of mass and the units of temperature and quantity used, because each unit appears as a factor an equal number of times in both numerator and denominator and consequently cancels out.

For a discussion of the specific heat of gases see Chapter VIII.

24. Calorimetry. A CALORIMETER is any piece of apparatus used to measure *quantity* of heat energy. This name is applied to a great variety of apparatus so that the only thing it designates is the use to which the article is put. Calorimeters are usually very simple copper vessels which may be protected from drafts, radiation, etc., by an outer vessel or jacket. Fuel calorimeters are frequently elaborate platinum-lined steel bombs. Steam calorimeters are sometimes little more than a steam pipe, with pressure gauge, valve and exhaust chamber containing a thermometer.

Calorimetry in a simple form is illustrated by the METHOD OF MIXTURES. The method gets its name from the fact that two substances like lead shot and water or iron and water are mixed together. These substances (or two quantities of the same substance) are at different but known temperatures before mixing. They are allowed to come to the same temperature after mixing and this temperature is determined.

The assumption is made that no heat is lost to outside bodies, and an equation is based upon this assumption. This equation may be written in either of two ways:

1. **Heat gained BY THE COLD BODIES = heat lost BY HOT BODIES.**

2. **Total heat IN ALL BODIES before MIXING = total heat IN ALL BODIES after MIXING.**

Total heat above 32° F. of any body = (its temperature Fahrenheit - 32°) × weight × its specific heat.

The first equation is the simplest to write except when steam is involved. Since some students in the class may already be in the habit of using this equation, it is preferable that all should use it in problems not involving steam.

In practice, the engineer most frequently employs the second style of equation in steam problems, because it is much more convenient. It is therefore suggested that the student habitually use this second type of equation for steam boiler and engine problems.

Engineers usually write this equation, using the total heat above 32° F. (or 0° C.), and this practice should also be followed by the student.

When this suggestion is carried out consistently, the student finds that in some problems he has to express heat in a body colder than the freezing temperature as a minus quantity. While there is no such thing as a minus quantity of heat, the expression has meaning when used to indicate the condition of a body having less energy in it than the body has at the standard temperature, 32° F.

25. Water Equivalent. The calorimeter itself always contains a certain amount of energy which may be expressed by its weight $\times$ specific heat $\times$ temperature, if its specific heat is known. The capacity of a calorimeter to absorb heat is therefore expressed by its weight times its specific heat. This product is known as the *water equivalent* of the calorimeter. Most calorimeters are made of sheet copper, nickel plated, and they usually have a specific heat approximately equal to .10. It is the *common practice* in ordinary laboratory work *to take the water equivalent* $= .10 \times \text{weight}$. No significant error results in any laboratory experiment when this practice is followed. Weigh the thermometer with the calorimeter and treat it as a part of the calorimeter.

If, however, extreme accuracy is desired, or the calorimeter is constructed of a variety of materials of unknown specific heat, the water equivalent may be found as in the determination that follows:

DATA

A calorimeter weighs..... 108.2 grams.
 Cold water is put in it when
 Calorimeter and cold water weighs 242.6 grams.
 Some hot water is prepared in a vessel directly above
 the calorimeter and kept at a temperature of
 100° C.
 Just before adding hot water observation is taken
 and:
 Temperature of calorimeter and contents before = 10.2° C.
 Hot water is at once added and after rapidly stirring,
 observations were made as follows:
 Temperature of calorimeter and contents after... = 31.6° C.
 Weight of calorimeter and contents after mixture = 288.1 grams.

COMPUTATIONS

Let the water equivalent of the calorimeter = x .
 The total heat in calorimeter and cold water was

$$[(x+134.4)+10.2] \text{ calories.}$$

The total heat in the hot water added was

$$[45.5 \times 100] \text{ calories.}$$

The total heat in the calorimeter and contents after mixing the
 hot and cold water must have been

$$[(x+179.9) \times 31.6] \text{ calories.}$$

Writing the total heat equation, we have

$$(x+134.4) \times 10.2 + 45.5 \times 100 = (x+179.9) \times 31.6.$$

Solving:

$$10.2x + 1371 + 4550 = 31.6x + 5685;$$

$$21.4x = 236,$$

$$x = 10.98 \text{ grams water equivalent.}$$

Just as in the above experiment, the *water equivalent is*

always added to the weight of the water in the calorimeter when water is used.

26. Precautions in Calorimetry. Not only in calorimetry by the method of mixtures, but in all calorimetry, variations in the numerical results may be due to causes falling under three classes:

(a) True errors resulting from careless work by the experimenters.

(b) Errors due to weakness in the method of experimentation.

(c) Variation in the quantities to be measured due to factors not under the control or under the observation of the experimenter.

ERRORS OF CLASS (a) must be reduced by the exercise of great care and attention to details. Each temperature reading and each weighing should be carefully inspected until the experimenter is sure that all *differences in weight* and all *differences of temperature* are known to the desired number of significant figures.

Among the errors of this class that the student should especially guard against and keep constantly in mind are the following:

1. Inaccurate reading of thermometers. The eye must be on a level with the top of the mercury column in the stem when readings are taken. The thermometer may be given a slight mechanical vibration to counteract the tendency for mercury to stick and go up or down by jumps.

2. Too great haste in taking temperatures. If temperatures are read too quickly, the thermometer does not have time to reach the temperature of its surroundings.

3. Taking the temperature of a part of a liquid or body. In case of a liquid this should be guarded against by thoroughly stirring immediately before reading the temperature.

4. Adding heat to the calorimeter or other apparatus by holding it in the hand, over a radiator, near a lamp, or

other body considerably warmer than the body itself. It is equally *important not* to take away heat *by placing the calorimeter on the table or iron base of ring stands, etc.* Wooden stands are provided upon which the calorimeter may be supported with very little metal surface in contact with the wood. If these with the calorimeter are placed inside an insulated chamber to cut off air drafts, the calorimeter will be well enough protected for ordinary purposes.

5. Loss of heat in transferring heated bodies to the calorimeter. This operation must be planned and practiced until it can be done quickly, neatly, and especially without the spilling of a drop of liquid.

6. Gain or loss of heat by transferring thermometers and stirring rods back and forth between apparatus at different temperatures. Thermometers enough should be used to enable the experimenter to keep one constantly in the calorimeter. The student may illustrate the result of carelessness in this matter by reading the room temperature with a *wet* thermometer and then with a *dry* thermometer.

ERRORS OF CLASS (b) may be avoided in part by the exercise of care and foresight. Under this head fall:

1. Correction for "water equivalent," which has already been discussed.

2. Corrections for inaccurate thermometers: For practical work, each thermometer should be standardized and occasionally checked against a reliable standard or by re-determining its fixed points. (See Experiments H 1-1 and H 1-3 and text on Thermometers.)

In experiments where differences in temperature only are required rather than exact temperatures, good results may follow from using an inaccurate thermometer provided it is evenly divided, of uniform bore, and the differences of temperature not great. In that case it will act like a differential thermometer. If two or more thermometers are used in the same experiment their scales should be compared,

and if any differences appear the readings should be recorded as observed. Later they should be corrected to values equaling those temperatures which would have been read if the most accurate thermometer had been used for all the readings.

3. Corrections for radiation. The calorimeter and contents may gain from surrounding bodies or may lose to these bodies heat due to radiation. (See Chap. VII.) This error may be largely eliminated by having the calorimeter and its contents as far below the room temperature during half the time the experiment is being conducted as it goes above the room temperature during the remainder of the time. To render this possible, it is usual to make a preliminary test to get in mind all the necessary details. If the rate of change of temperature is fairly constant during the experiment, the loss in one half the time will equal the gain in the other half and no significant error will result. This means of correction should always be taken unless conditions forbid it.

Whenever the method given above is not convenient, a radiation curve should be plotted and corrections made from it. When this is carefully done, the error due to radiation will usually be corrected with great accuracy.

The following experiment will illustrate this:

DETERMINATION OF THE SPECIFIC HEAT OF ALUMINIUM

The laboratory directions for Experiment 32-1 were followed in every particular. After the aluminium was heated in a steam-jacketed chamber, readings of the thermometer were taken every half minute for five minutes and a curve plotted, as shown in the figure, from which to correct for radiation.

The following is an extract from the laboratory direction sheet for Experiment H 2-1:

DETERMINATION OF THE SPECIFIC HEAT OF A SOLID

The method here given is known as the "Method of Mixtures." The solid at some convenient temperature is placed in a known quantity of water at a different temperature, and the two allowed to come to a common temperature.

Data to be taken include: (a) Mass of solid; (b) mass of water; (c) temperature of solid before it is placed in water; (d) temperature of water; (e) temperature of mixture. Correction must be made for any heat absorbed or given out by the calorimeter, which undergoes the same temperature changes as the water, and some means must be employed to correct for gain or loss of heat through radiation.

Weigh the solid, then suspend it in the vessel to be heated.

In the meantime, put into a calorimeter enough water * cooled to 3° or 4° below the temperature of the room, to cover the solid.

Stir the water in the calorimeter thoroughly and take the temperature. Determine also the temperature of the solid in the heater. Quickly transfer the solid to the calorimeter. Stir the water until the temperature ceases to rise, and record the highest temperature.

From your data compute the specific heat of the solid, making proper corrections for the water equivalent of the calorimeter and for any errors of thermometers used. Make three determinations, taking the average. Write complete "heat equations" for each computation.

DATA

Metal used, *Aluminium*.

Weight, 184 gms.

Thermometer: In calorimeter—Special $20-35^{\circ}$.

In hot water— 60° Y.

Calorimeter No. Weight 108.2. Water equivalent 11.0 gms.

Weight of calorimeter and cold water, 304.6. Weight of cold water, 196.4. Temperature of hot metal, 99.6° C.

* The exact amount of water to be used and its temperature will depend upon the kind and weight of solid used. The conditions should be such that the temperature of the water in the calorimeter after adding the solid shall be as much above the room temperature as it was below it before adding the solid. Further correction for radiation will then be unnecessary. A preliminary test or two should be made to determine the amount of cold water, and the temperature which will best give these conditions.

Time.	Temp. of Cold Water.	Time.	Temp. of Cold Water.
0	20.24	3	32.73
$\frac{1}{2}$	24.68	$3\frac{1}{2}$	32.56
1	29.12	4	32.39
$1\frac{1}{2}$	32.85	$4\frac{1}{2}$	32.13
2	32.91	5	31.98
$2\frac{1}{2}$	32.86		

The solid line in Fig. 9 represents the actual readings.

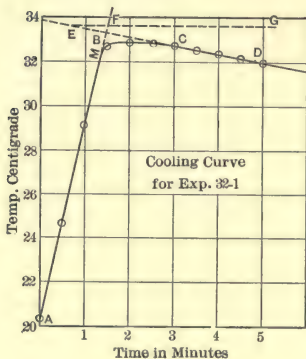


FIG. 9.

Curve *CD* is a short radiation curve for the calorimeter and is projected upward to *BE* in the direction that the curve would probably have taken if at zero time the calorimeter had been at a somewhat higher temperature than the maximum reached during the experiment. *AMB* is the curve that might have resulted if the transfer of energy had gone on at a uniform rate until complete and the temperature of the water had been instantly indicated on the thermometer. *B*, the intersection with the radiation

curve, and *AM* extended, would then have been the first point on the radiation curve.

The slope of the curve *BD* at *B* gives the velocity of cooling (due to radiation, etc.) at *B*. The mean velocity of cooling (due to radiation, etc., and tending to reduce the rise in temperature), between *A* and *B* is only half of this. However, we assume that the amount of the losses due to radiation, etc., is in proportion to the difference in temperature between the vessel and its surroundings. (See Chap. IX.) On this assumption, the correction for radiation, etc., might be taken as half the rate at *B* $\times$ the time to arrive at *B* counted from the beginning of the experiment. Mathematically, this is exactly equal to the rate at *B* $\times$ half the time. If, then, we project *DCB* backward to the

point E , which has an abscissa half as large as B , we have the equivalent of this mathematical process. The point E will represent the temperature that would have been reached and maintained indefinitely if there had been no lost energy due to radiation, convection, conduction, etc.

The actual ordinate of E obtained by carrying this out graphically to a large scale is 33.70°C . From this value and the data given above we can write our heat equation:

Let X = specific heat of aluminium.

Heat gained = heat lost.

$$(196.4 + 11)(33.70 - 20.24) = 184(99.6 - 33.7)X,$$

$$207.4 \times 13.46 = 184 \times 65.9X,$$

$$X = .230.$$

The corresponding total heat equation would be

$$\begin{aligned} (196.4 + 11)20.24 + 99.6 \times 184 \times X \\ = (196.4 + 11)33.70 + 33.70 \times 184 \times X. \end{aligned}$$

4. Evaporation of water. This loss will be better understood after a study of latent heat. It is not significant if the temperature of the water used is below 40°C ., if the calorimeter is covered, and if the time of the experiment is short. If other liquids than water are used, they should also be kept well below their boiling-point if errors due to evaporation are to be avoided. The "radiation curve" corrects for this loss also.

It appears from the foregoing discussion of errors of class (b) that *foresight* and *care* must be exercised to insure accurate results in heat experiments. This is also true of errors of class (c).

(c) DEVIATIONS: Variations in the quantities to be measured due to the fluctuations in the properties of the substances studied should be anticipated and detected if possible. Thus fuel calorimetry is resorted to in order to detect the variations in energy per pound of coal or other fuel. Devia-

tions in specific heat of substances result when the temperature is changed, when the structure or state is changed, and when even small per cents of impurities are introduced. As an illustration of such deviations look up carbon, water, mercury, etc., in the specific heat tables.

27. Other Methods. Numberless other so-called "methods" are used. They all differ as to the details of construction of the calorimeters and the particular ways that are devised to reduce the deviations and errors discussed in the previous section. The student will find that if he examines the manipulation of any particular calorimeter and the computation of the results with the points already discussed in mind, no special difficulty will be found.

Special calorimeters and their use are described in the chapter on instruments.

Problem 12A. Suppose we mix in a tank 40 lbs. of water at 120° F., and 60 lbs. of water at 35° F., what will be the resulting temperature?

Let x = the final temperature.

Heat gained by 60 lbs. = heat lost by 40 lbs.

$$60(x - 35) = 40(120 - x),$$

$$[60x - 2100 = 4800 - 40x,$$

$$100x = 6900$$

$$x = 69^\circ.$$

The corresponding "total heat" solution is

Each pound at 120° F. contains 88 B.T.U., total heat above 32° F., so 40 lbs. contains $40 \times 88 = 3520$ B.T.U. Similarly, at 35° F. each pound contains only 3 B.T.U. and 60 lbs. $3 \times 60 = 180$ B.T.U.

Total B.T.U. above 32° F. in mixture is therefore $3520 + 180 = 3700$ B.T.U.

Total weight of mixture = 100 lbs.

Temperature above 32° F. of mixture = $3700 \div 100 = 37^\circ$ F.

Therefore the final temperature of mixture = 37° F. + 32° F. = 69° .

Problem 13. It is desired to find the temperature of a furnace. A piece of fire-clay (sp. heat .22) weighing 4 lbs. is placed in a furnace until it comes up to the temperature of the furnace. It is then dropped into a pail containing 20 lbs. of water at 40° F. The water then rises to 120° F. What is the temperature of the furnace?

Let t = the furnace temperature.

Heat gained = heat lost,

$$20 \times (120 - 40) = .22 \times 4(t - 120),$$

$$.88t - 105.6 = 20 \times 80,$$

$$.88t = 1706,$$

$$t = 1938.$$

The corresponding total heat solution is:

Before mixture:

Total heat in water above 32° = $20 \times 8 = 160$ B.T.U.

Total heat in clay above 32° = $4 \times .22 \times (t - 32)$ B.T.U.

After mixture:

Total heat in water above 32° = $20 \times 88 = 1760$ B.T.U.

Total heat in clay above 32° = $4 \times .22 \times 88 = 77$.

Since the quantity of heat energy has not changed

$$160 + 4 \times .22 \times (t - 32) = 1760 + 77,$$

$$.88(t - 32) = 1677,$$

$$.88t - 28 = 1677,$$

$$.88t = 1705,$$

$$t = 1938.$$

Problem 14. If 5 lbs. of water at 200° F. are mixed with 12 lbs. at 50° F., what is the resulting temperature?

Problem 15. A copper calorimeter weighs 120 gms. It contained 400 gms. of water at 12° C. Into this was dropped 800 gms. of pure nickel at 100° C. Find resulting temperature.

Problem 16. A copper calorimeter weighs .88 lb. In it is placed 5.81 lbs. of water. A piece of aluminium at 100° C. weighing 7.41 lbs. was dropped into the water, which was at 10.2° C., and the temperature of the mixture was 29.4° C. Find the specific heat of aluminium?

Problem 17. 9.07 gms. of benzine are burned in a fuel calorimeter containing 18.20 lbs. of water and having a water equivalent of .80 lb. The initial temperature of the water was 71.27°F. , and the final temperature was 91.82°F. Find the B.T.U. per pound of this sample.

Problem 18. A 1-gm. sample of coal is burned in a fuel calorimeter having a water equivalent of .56 lb., and containing 2.08 lbs. of water. The original temperature was 67.89°F. , and the final temperature was 81.24°F. Find B.T.U. per pound.

Problem 19. A 1-gm. sample of coal is burned in a fuel calorimeter which was made of 820 gms. of copper and 4230 gms. of steel. It contained 4820 gms. of water at 21.87°C. before the fuel was burned and the temperature increased to 23.41°C. Find calories per gram of coal.

Problem 20. 1.22 cu.ft. of gas (measured under standard conditions) was burned in a fuel calorimeter containing 8.12 lbs. of water and having a water equivalent of .58 lb. The products of combustion and radiation carried away 4.2 B.T.U. The temperature before the run was 62.1°F. , and after the run was 91.8°F. Find B.T.U. per cubic foot.

REVIEW PROBLEMS, CHAPTER III

21. Show that the specific heat is the same whatever the system of weights and whatever the temperature scale used.

22. An iron ball weighing 6 lbs. is heated in boiling water at 212° F., and then dropped into 4 lbs. of water at 35° F. Temperature rises to 60° F. What is specific heat of the iron?

23. 10 lbs. of water at 180° F. are poured into a copper beaker weighing 2 lbs. and containing 8 lbs. of water at 50° F. What is resulting temperature? (Sp. heat copper = .095.)

24. An aluminium block weighing 150 gms. at a temperature of 100° C. is dropped into a copper beaker weighing 200 gms., and containing 400 gms. of water at 10° C. Resulting temperature is 16.4° C. What is specific heat of aluminium?

25. Two pounds of aluminium at 50° F., 4 lbs. of copper at 100° F., and 10 lbs. of cast iron at 200° F., are all simultaneously plunged into 3 cu.ft. of water at 40° F. What is the final temperature of the mixture?

26. One gram of coal was tested in a Thomson calorimeter whose total water equivalent was 2120 gms. The initial and final temperatures of the apparatus were 54.00° F., and 60.85° F. What was the calorific value of the coal?

27. A boiler containing 5 tons of water at a temperature of 200° F. is supplied with water at 60° F. from a feed-pump delivering 20 gals. per minute. If the pump be kept running for ten minutes, what will be the resulting temperature of the boiler?

28. A number of brass condenser tubes weighing 540 lbs. were at a temperature of 58° F. before the condenser was at work; afterward, when in use, the mean temperature was 110° F. How many B.T.U. did they take up?

29. What weight of water is the metal in the above problem equivalent to with respect to its capacity for heat?

30. A cast-iron plate weighing 120 lbs. is immersed in 240 lbs. of water. If the temperature of the plate is 150° F., and that of the water 50° F., what would be the final temperature (t) of both?

31. If coal were pure carbon it would take $2\frac{2}{3}$ lbs. oxygen per pound of coal to burn it to carbon dioxide (CO_2). If air contained 20 per cent by weight oxygen and 80 per cent nitrogen,

and if the products of combustion are 400°F . hotter than the cold air supply when they go up chimney, how many B.T.U. do they carry away?

32. If 50 per cent excess of air is supplied, how many B.T.U. will be carried away. In Problem 31?

33. If the heat of combustion of the carbon in Problem 31 were entirely used to heat the gaseous products (i.e., assuming no losses from radiation, conduction, and convection during the burning), what would be the resulting temperature of these products?

34. If 50 per cent of air were used in Problem 33, what would have been the resulting temperature?

35. If 2.46 lbs. of pure oxygen and 1 lb. of acetylene produce complete combustion, and if the specific heat of the gaseous products = .240, what would be the resulting temperature if no heat were lost? Assume the acetylene and the oxygen to be at 0°C .

36. In Problem 35, find the resulting temperature if the necessary oxygen is supplied from air.

NOTE. Unless otherwise stated, assume 23 per cent by weight oxygen and 77 per cent nitrogen in air.

37. One pound benzine requires 2.46 lbs. of oxygen for complete combustion. What is the highest temperature obtainable with benzine and oxygen under the same assumptions as in Problem 35?

38. Under conditions as in Problem 37, what temperature could be obtained by burning benzine and air?

39. If 50 per cent excess of air and benzine were used in Problem 37, what temperature would result?

40. How many cubic feet of dry air at 32°F . will 1 lb. of coal containing 14,000 B.T.U. warm to 72°F ?

(1 cu.ft. air weighs .0817 lb.)

41. A room $12 \times 16 \times 8$ originally at 32°F ., has burned in it 1 cu.ft. of gas giving 600 B.T.U. If escaping air is at the same temperature as that remaining at the completion of the combustion, find temperature of air.

42. A piece of fire-brick weighing 2.83 lbs. is to be used to determine a furnace temperature. In order to establish its average specific heat for the range over which it was to be used, it was heated in an oven whose temperature was known to be 1950°F . and then dropped into 19.8 lbs. water at 40.6°F . If the resulting temperature of the water was 100.8°F ., find the specific heat of the brick.

(Water equivalent of the calorimeter, stirrer, thermometer, etc., was .4 lb.)

43. If for every pound of coal burned under a steam boiler 12 lbs. of gaseous products go up the flue at a temperature of 600°F. , find the energy carried away in B.T.U. per lb. if the boiler-room temperature is 60°F.

(Assume specific heat of gas to be .237.)

44. What fractional part of a horse-power hour would this energy be if it could be saved and made to do useful work?

45. If 2 lbs. of steam is allowed to go through the fire along with the air to prevent the formation of too large masses of coke, how much additional energy is taken from the fire by the steam if air escapes up the flue at a temperature of 600°F. ?

(Specific heat of steam .500.)

46. If an air-cooled gasoline engine has an efficiency of 20 per cent it is clear that 80 per cent of the energy in the fuel must be either carried off from the exhaust or "radiated" from the cylinder. A certain engine burns 24 lbs. of liquid fuel per hour, containing 19,500 B.T.U. per pound; for every pound of fuel 19 lbs. of air was also put through the cylinder. If the air was taken in at 60°F. , and the temperature of the exhaust was 780°F. , how much energy passed out via the exhaust? How much was left to be radiated off per hour if the combustion was complete?

(Assume specific heat of gases in exhaust equal to .237.)

47. If in the engine referred to in the previous problem, 60 per cent of the energy in the fuel was "radiated" from the surface of the cylinders, how many pounds of air must have been heated from 60°F. to 180°F. per hour?

(Specific heat of air .237.)

SUMMARY, CHAPTER III

THE SPECIFIC HEAT of a substance is the capacity of a unit mass of the substance to take up heat energy. The specific heat of a substance is the quantity of heat energy required to raise a unit mass one degree.

$$\text{Sp.H.} = \frac{\text{B.T.U. added}}{\text{Weight in pounds} \times \text{rise in temperature in F. deg.}}$$

$$\text{Sp.H.} = \frac{\text{Calories added}}{\text{Weight in grams} \times \text{rise in temperature in C. deg.}}$$

CALORIMETERS are instruments with which quantity of heat energy is measured. **Calorimetry** is the name given to the process of measuring energy with a calorimeter.

In the method of mixtures, **HEAT EQUATIONS** are written based upon the assumption that no energy is lost during the period of manipulation.

(1) Heat gained = heat lost.

(2) Total heat before mixing = total heat after mixing.

These equations with only slight variation apply to other methods.

ACCURACY in calorimetry depends upon careful attention to many small details, such as accuracy of thermometer readings, accuracy of weighings, and corrections for water equivalent, radiation, conduction, convection, and evaporation.

THE WATER EQUIVALENT is usually taken as $\frac{1}{10}$ of the weight of copper calorimeters and represents the amount of water which would have an equivalent capacity for taking up heat.

CORRECTIONS for radiation, conduction, and convection may be avoided in many cases by starting with the calorimeter (and contents) as far below room temperature as it is to be heated above room temperature. Evaporation may be neglected in most cases where the water is below 40° C.

CHAPTER IV

EXPANSION

28. Expansion of Solids. It is a matter of common experience that in general when bodies are heated they expand. Trolley and telegraph wires sag noticeably more in summer than in winter. In making patterns for the foundry an allowance must be made for the contraction of the metal when it cools if the casting is to be made an exact

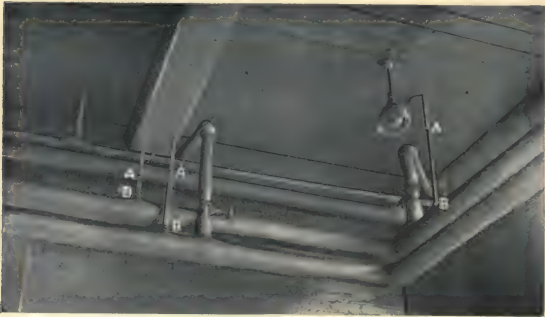


FIG. 10.—Steam Piping, Showing Method of Suspension.

size. Patternmakers frequently use rules too long by $\frac{1}{8}$ in. to the foot. Compensator pendulums are placed on clocks and compensated balance wheels in watches to correct for the effect of expansion. The amount of this effect varies for each substance and, if the texture of the body is not uniform in all parts and in all directions, the amount of the effect may vary in the three directions in the body itself.

Thus wood has a much greater expansion with the grain than across the grain. A crystalline substance may have a different rate of expansion along each of the several axes.

The effect of expansion is taken into consideration in countless practical cases where it is not necessary to make any accurate computation of the amount of the effect. Fig. 10 shows the steam main which runs along the ceiling of the Pratt Institute machine shop and supplies steam



FIG. 11.—Brooklyn Bridge Expansion Joint.



FIG. 12.—Rail Expansion Joint on Brooklyn Bridge.

heat to the electrical laboratory above. It will be seen that this piping is suspended by a three-piece strap jointed at *A* and *B* so that, as the steam changes the temperature of the iron pipe, expansion can take place without injury to the supporting straps or to the pipe.

In Figs. 11, 12, and 13 is shown an expansion joint of the Brooklyn Bridge. This joint is intended to care for the expansion due to the stretching under varying loads as well as the thermal expansion. It will be noticed from Fig. 12 (a view of the elevated tracks from the front of an elevated train) that the elevated and trolley tracks are provided with a long, wedge-shaped lap which allows for a relative movement of several inches, as the two sections slide by each other. To the left of this may be seen the break in the third rail.

Fig. 13 shows the joint as seen from the bridge promenade.



FIG. 13.—Expansion Joint on Brooklyn Bridge.

S telescopes into *G* and keeps the bridge members in line. The two ends of the bridge section *M* and *N* are supported by the suspension cables *A* and *B*. Fig. 11 shows this construction more clearly as the casing *G* is removed.

While in the majority of cases where an allowance is made for thermal expansion the amount is so small that no computation is attempted, yet it may be accurately found, if desired.

For purposes of comparison and practical computation it is convenient to know the increase in length per unit

length per degree, and a table at the back of the book gives a number of these rates under the heading, COEFFICIENT OF LINEAR EXPANSION.

The coefficient of linear expansion of a solid =

$$\frac{\text{Increase in length}}{\text{Original length} \times \text{rise in temperature}}.$$

This quantity is usually determined for the range of temperatures from freezing to boiling of water, and the average value given.



FIG. 14.—Coefficient of Expansion Apparatus.

It is important to notice that the unit of length used appears once each in both numerator and denominator and therefore does not affect the numerical value of the coefficient. But the unit of temperature appears only in the denominator, and therefore there is a different numerical value of the coefficient for each temperature scale in use. Accordingly when the coefficient is stated the temperature

unit in which it is determined must also be stated. Also if, like wood, the substance has more than one linear expansion, it is necessary to state in which direction the expansion takes place.

In Experiment H 1-1, the coefficient of linear expansion is determined. Fig. 14 shows the apparatus, which consists of a metal rod soldered into an outer jacket, *A*. This jacket is steam heated from the steam main through the hose *B*. Hose *C* is connected to the drain pipe so that the water that is condensed in the jacket *A* will be allowed to escape. The temperature of the rod is read from the thermometer *T* before the steam is turned on, and again after the steam has heated the rod to its own temperature. The increase in length is read from the micrometer, *M*. *P* is a telephone receiver used to tell when the micrometer makes contact with the metal.

The following is an extract from the laboratory direction sheets.

Experiment H 1-1. Determination of the Rate of Increase in Length of a Solid on Application of Heat.

The amount of increase of a solid for ordinary ranges of temperature is very slight. Delicate means of measurement are therefore necessary. One very common method makes use of a micrometer screw. The metal tested, in form of a rod, is held firmly in a special frame, with one end pressed tightly against a stop. A micrometer screw is mounted upon the frame in such a position that it may be brought in contact with the other end of the rod.

First measure the length of the rod at room temperature. In doing this it is not necessary to remove the rod from the jacket. Take jacket and all from the support and place it on the desk beside a meter stick. Place blocks against the projecting ends of the rod and against the meter stick. Read positions of inside edges of blocks.

Record the reading of the thermometer in the jacket, and the reading of the micrometer when in contact with the rod. This reading will be taken by turning up the micrometer until a click is heard in the telephone receiver shown in Fig. 14. *Turn the micrometer screw back a fraction of a turn to zero, and then one whole turn to give the rod space to expand. Do this carefully so that you will be able to compute accurately the difference between this first or zero reading and the second reading taken when hot.*

Then connect with the steam main and pass steam through the

jacket until the thermometer ceases to rise. Read thermometer and micrometer.

The following is a set of data obtained from one of these pieces of apparatus.

DATA

Kind of rod.....	Aluminium
Length of rod.....	24.5 ins.
Temperature of rod cold.....	21.0° C.
Micrometer reading cold.....	.0273 in.
Micrometer turned back to zero and then one whole turn	} 101.8° C.
Temperature of rod hot.....	
Micrometer reading hot.....	.0334 in.

COMPUTATIONS

Rise in temperature of rod.....	80.8° C.
Micrometer was turned back.....	.0273 + 50 = .0773 in.
Micrometer was advanced.....	.0334 in.
Elongation of rod.....	= .0773 - .0334 = .0439 in.
Elongation per inch.....	$\frac{.0439}{24.5} = .00179$ in.
Elongation per inch per degree C... ..	$\frac{.00179}{80.8} = .0000221$ in.

29. Coefficient of Expansion of an Area. If a substance is homogeneous we may expect a surface of it to expand uniformly both in length and in breadth. Its increase in area may be computed in this case from its linear coefficient. A square surface having unit sides, when expanded would have each side increased by (at) where (a) is the linear coefficient and (t) the rise in temperature. The expanded length of each side would then be ($1+at$) and the area, $(1+at)^2$.

Removing parentheses we have $\text{area} = 1 + 2at + a^2t^2$ and the increase in area $= 2at + a^2t^2$.

For most computations it will be found that a^2t^2 is a quantity too small to be taken into consideration, as (a)

is usually smaller than $\frac{1}{10,000}$ and therefore a^2 is smaller

than $\frac{1}{100,000,000}$. Since the error in dropping the last term is practically always less than one part in a thousand, we can always take the coefficient of twice the coefficient of linear expansion.

The coefficient of areal expansion of any substance =

$$\frac{\text{Increase in area}}{\text{Original area} \times \text{rise in temperature}}.$$

30. Coefficient of Cubical Expansion. In a homogeneous solid we can compute the increase in volume in a similar way to that just employed to compute the area of a face of the solid. In this case let us assume a cube having sides of unit length.

$$\text{When cold the volume} = (1)^3 = 1;$$

$$\text{If expanded, the length of each side} = (1 + at);$$

$$\text{and the volume} = (1 + at)^3.$$

$$\text{Removing parentheses, the volume} = 1 + 3at + 3a^2t^2 + a^3t^3.$$

$$\begin{aligned} \text{Subtracting the original volume, the increase in volume} \\ = 3at + 3a^2t^2 + a^3t^3. \end{aligned}$$

But $3a^2t^2 + a^3t^3$ can be neglected because it is too small to be significant. Then we can always take the COEFFICIENT OF CUBICAL EXPANSION AS THREE TIMES THE COEFFICIENT OF LINEAR EXPANSION.

The Coef. of Cubic Expansion of any substance =

$$\frac{\text{Increase in Volume}}{\text{Original Volume} \times \text{Rise in Temp.}}$$

In tables only the linear coefficients of solids are given.

These tables are sometimes made out to show expansion for an increase in temperature of 1° C., and sometimes for an increase in temperature of 1° F. Since the centigrade degree represents $\frac{9}{5}$ as much increase in temperature as 1° F., and therefore $\frac{5}{9}$ the expansion, to change a Fahrenheit coefficient to a centigrade coefficient, multiply by $\frac{5}{9}$. The table in the appendix is given in centigrade. To change to the Fahrenheit coefficient, it will be necessary to multiply by $\frac{9}{5}$.

31. Expansion of Liquids. Cubical expansion, as already defined, takes place in liquids. This quantity, however, is not so easily determined for a liquid as for a solid, because it is always necessary to correct for the expansion of a retaining vessel. Thus, if a liquid such as water is contained in a vessel of glass, the vessel may increase in volume either faster or slower than the water in the vessel. So apparently the water may either expand or contract.

By measuring the apparent increase in volume of the liquid in the vessel, giving it a minus sign if it is a contraction, and dividing by the original volume and the rise in temperature, we have what is called the apparent coefficient of cubical expansion. The apparent cubical coefficient of expansion of the liquid added to the cubical coefficient of the vessel will give the absolute coefficient of cubical expansion of the liquid.

The Apparent Coef. of Cu. Expansion of a Liquid in a Vessel =

$$\frac{\text{Apparent Increase in Vol.}}{\text{Apparent Original Vol.} \times \text{Rise in Temp.}}$$

The Apparent Coef. of Cu. Expansion + Coef. of Cu. Expansion of the Vessel = Absolute Cu. Coef. of the Liquid.

This is a correct statement to just the same degree as the statement that the cubical coefficient of expansion is 3 times the linear coefficient. It should also be remembered that these coefficients are

always an average value over a specified range of temperature. They are never based on the rate of expansion at a fixed or standard temperature.

Problem 1. Two trolley poles 120 ft. apart are strung with copper wire. If the coldest winter's day is 40° F. below zero, and if the thermometer read 80° F. when the line was erected, how much will it draw in cold weather? (Disregard its elasticity and allow no slack.)

From table:

Coefficient of expansion of copper in centigrade system, .0000168
Coefficient in Fahrenheit system will be

$$.0000168 \times \frac{5}{9} = .00000933.$$

If 1 ft. expands .00000933 ft. in a rise of 1° F., 120 ft. will expand $120 \times .00000933 = .0011196$ ft.

If cooled 1° it will contract an equal amount. But the wire will have cooled 120° F. when the temperature reaches -40° F. Therefore 120 ft. will contract.

$$120 \times .000112 \text{ ft.} = .0134 \text{ ft., or } .1608 \text{ in.}$$

Problem 2. If 50-ft. steel rails are laid when the temperature is 40° F., how much space must be left between each pair, assuming highest summer temperature to be 110° F.? (Disregard the elasticity of the steel and assume:

Coefficient of expansion for this steel = .0000123.

This means that one centimeter of steel expands .0000123 of a centimeter when heated 1° C., or 1 ft. expands .0000123 of a foot, or 1 in. expands .0000123 of an inch.)

To reduce to Fahrenheit:

$$.0000123 \times \frac{5}{9} = .00000685.$$

If 1 ft. expands .00000685 ft. for a rise of 1° F., 50 ft. will expand $50 \times .00000685 \text{ ft.} = .000343 \text{ ft.}$

But the rise in temperature is $110 - 40 = 70^{\circ}$ F., therefore, 50 ft. will expand $70 \times .000343 \text{ ft.} = .0240 \text{ ft.}$

$$.0240 \text{ ft.} = .288 \text{ in.}$$

Therefore the rails should be laid .288 inch apart to avoid buckling in summer.

Problem 3. In Problem 2, what would have been the force of compression in the rail if its cross-sectional area was 4.2 sq.in., if its modulus of elasticity was 24,000,000, and if the ends of the rails were riveted together at the temperature stated?

The rail was compressed, and therefore under a strain of

$$\frac{.0240 \text{ ft. (total elongation)}}{50 \text{ ft. (total length)}} = .00048 \text{ of a foot per ft.}$$

$$\frac{\text{stress}}{\text{strain}} = \text{modulus.}$$

Let x = the stress (per square inch). Then

$$\frac{x}{.00048} = 24000000,$$

$$x = 24000000 \times .00048 = 11520 \text{ lbs. per sq.in.}$$

$$\text{Total force of compression} = 4.2 \times 11520 = 48400 \text{ lbs.}$$

Problem 4. A full glass vessel contains 400 gms. of mercury at 0° C. How much would it hold at 100° C.?

$$\text{The apparent coef.} = .000182 - 3 \times .00000833.$$

The apparent increase in volume or the overflow of mercury
 $= (.000182 - .0000250) \times 400 \times 100 = 6.28 \text{ gms.}$

$$\text{Therefore there will remain in the vessel } 400 - 6.28 = 393.72 \text{ gms.}$$

Problem 5. How much will a 12-ft. iron boiler tube expand in length when heated from 40° to 300° F.?

Problem 6. How much will a 300-ft. span of a steel bridge vary in length owing to the change from a summer temperature of 110° F. to a winter temperature of -10° F.?

Problem 7. Surveyor's chain 66 ft. long at 60° F. is used in zero weather to measure a mile. What length must be added to a measured mile to have a true mile?

Problem 8. What change takes place in the cubical capacity of a quartz glass cylindrical pendulum bob containing mercury and holding 10 c.c. at 20° C. if heated to 50° C.?

Problem 9. A steel rod 1.64 ins. in diameter is to be used to draw the walls of a building together. If the rod is heated to 240° F., what tension can it exert in cooling to 75° F.?

$$\text{Coefficient of expansion of steel} = .000011,$$

$$\text{Coefficient of elasticity of steel} = 30,000,000.$$

Problem 10. A steel tie of 8 sq.ins. cross-section area is to be used to draw the bulging walls of a building together. When heated up to 400° , the ends are fastened to the wall and the rod is allowed to cool to 100° F. With what force does it tend to draw the building together? (Use same coefficient as above.)

32. Expansion of Gases. Gases, being fluid, have *no definite volume*. Unlike liquids, gases have an *extremely variable volume*.

The volume of a gas depends among other things upon the pressure upon it. Thus 1 lb. of a gas such as air under "standard atmospheric conditions," (under 760 mm. of mercury pressure and at the freezing temperature of water), would occupy 12.39 cu.ft. If kept at the same temperature, and the pressure is increased by 168 lbs., the volume becomes almost exactly 1 cu.ft. If the pressure were allowed to drop to a quarter of a pound, the volume required if the gas were kept at freezing temperature would be approximately 182 cu.ft. Whatever the volume allotted to the pound of gas, it would tend to expand and fill it *uniformly*. The relation that exists between the *pressure* and the *volume* of a gas *kept at a fixed temperature*, is expressed by **Boyle's Law**, which is:

THE PRESSURE OF A GAS VARIES INVERSELY AS THE VOLUME WHEN THE TEMPERATURE REMAINS CONSTANT.

Keeping in mind that this relation holds only for changes at a fixed temperature, this may be more briefly written:

PRESSURE $\times$ VOLUME = CONSTANT, or in symbols:

$$P \times V = \text{CONSTANT.}$$

When a gas expands (and contraction we can call negative expansion) according to Boyle's law, the gas is said to undergo "**Isothermal Expansion.**" (See also p. 202.)

Distinct from isothermal expansion we want to consider the expansion of gases due to changes in temperature. In order that we may keep the conditions as simple as possible,

at first we will consider only changes that take place at constant volume or at constant pressure.

Suppose then that we were to take 1 lb. of air and keep it at atmospheric pressure but vary its temperature and volume in suitable apparatus. The resulting data plotted on curve paper are given in Fig. 15. The curve is a straight line, but does not pass through the origin. From this we see that there is a constant increase in volume for each rise of 1°C . The volume at 0°C . is 12.39 cu.ft., and the volume increases to 37.17 cu.ft. at 546°C . Thus for a rise in temperature of 546°C . an increase in volume of 24.78 cu.ft. takes place. Originally at 0°C . there was 12.39

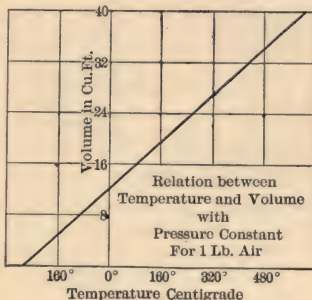


FIG. 15.

cu.ft., so there has occurred an increase of 2 cu.ft. for each cubic foot originally at 0°C . The rate of increase per cubic foot per degree would therefore be $\frac{2}{546}$ or $\frac{1}{273}$.

This means that the air increases $\frac{1}{273}$ (or 0.00366) its volume at 0°C . for every rise of 1°C . anywhere on the scale. This quantity is called the coefficient of expansion of a gas at constant pressure.

Exp. H 1-2 discussed on p. 80 shows how this quantity is determined in the laboratory.

This coefficient is a cubical coefficient, since it is a coefficient of change of volume, and therefore in any experimental use of it much the same precautions must be taken as in the case of the cubical expansion of a liquid. However,

this difference must be clearly understood. The numerical value of the coefficient is many times larger than the coefficient for a liquid; therefore its importance in computing gas volumes is proportionately increased. Errors must be avoided by applying more exact methods of computation. Accordingly it is always necessary to apply the coefficient to the volume of a gas at 0°C. , else the correction will be too large or too small, according to the initial temperature. Thus we see by again referring to the curve, Fig. 15, that 1 lb. of air always increases $\frac{24.78}{546}$ or .0454 cu.ft. per degree.

Also $\frac{1}{273}$ of 12.39 cu.ft. = .0454 cu.ft. Now if we take $\frac{1}{273}$ of any volume above 0°C. we get a quantity larger than .0454, and if we take the volume for any temperature below 0°C. , we get less than .0454 cu.ft.

This same coefficient results if data are taken and plotted for other pressures besides that used in plotting Fig. 15. *We may then say that the increase in volume is in proportion to increase in temperature when the pressure is cons'an'.* This fact is usually called CHARLES' LAW, and is stated thus:

The coefficient of expansion of a perfect gas is independent of the pressure if the pressure is constant.

Air, nitrogen, oxygen, hydrogen, and a few other gases obey this law rather closely.

The above facts may be set forth in a formula of typical form. If V_t = the volume at any temperature, $t^{\circ}\text{C.}$, V_0 the volume at 0°C. , the freezing-point of water, and a = the centigrade coefficient of expansion, then

$$V_t = V_0(1 + at).$$

This coefficient worked out for the Fahrenheit scale is $\frac{1}{493}$, and care must always be taken to use, as the basis

for computation, the volume at the freezing-point of water. The formula has the same form, being $V_t = V_{32}(1 + at')$ (when $t' = t - 32$) but a has a different numerical value).

33. Pressure Effects Due to Change of Temperature at a Constant Volume. If 1 lb. of a perfect gas be kept at a constant volume of 12.39 cu.ft. and its temperature varied, the resulting data will plot into a curve similar to Fig. 16.

It will be seen that this curve closely resembles that of Fig. 15, and shows that the pressure varies directly as the temperature when the volume is constant.

If the rate of increase of pressure be determined by finding the slope of the curve we find that again we get the fraction $\frac{1}{273}$ if we take the pressure in atmospheres. In this case

we can again take $\frac{1}{273}$ (or .00366) as the coefficient of expansion if we keep in mind that this fraction expresses the increase in pressure as a fractional part of the pressure at the freezing-point of water.

The coefficient of expansion of a gas at constant volume is the increase in pressure per degree rise in temperature, divided by the pressure at freezing-point of water.

This coefficient is determined in Exp.

H 1-3, which is discussed in full on p. 86.

Just as in the case of expansion at constant volume, care must always be exercised to apply the coefficient to the condition of the gas at freezing-point of water.

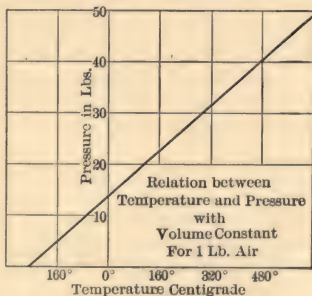


FIG. 16.

The equation by which the relation between the pressure of a gas at constant volume and varying temperatures is expressed, follows:

$$P_t = P_0(1 + at);$$

where

P_t = the pressure at t° centigrade;

P_0 = the pressure at 0° centigrade;

and

a = the coefficient of expansion at constant volume.

Similarly, the equation for use when the temperatures are in Fahrenheit degrees is

$$P_t = P_s(1 + at'),$$

where $t' = t - s$ or the amount that t is above or below the standard temperature.

It will be noticed that this expression has the same form as $V_t = V_0(1 + at)$ and is also like the equation which gives the resistance R_t of a conductor at any temperature t as compared to the resistance R_s at a standard temperature s , when t' is the difference between t and s

$$R_t = R_s(1 + at').$$

All of these formulæ are applicable whether the Fahrenheit or centigrade scale is used, provided a proper coefficient is taken.

The use of these formulæ is illustrated by the problems at the end of the next section.

Problem 11. If 3.5 lbs. of nitrogen has a volume of 43.8 cu.ft. at 0° C., what is its volume at 20° C.?

$$V_t = V_0 \left(1 + \frac{1}{273} t \right),$$

$$V_{20} = 43.8 \left(1 + \frac{1}{273} \times 20 \right),$$

$$V_{20} = 43.8 \frac{(293)}{(273)},$$

$$V_{20} = 47.0 \text{ cu.ft.}$$

Problem 12. If 72 cu.ft. of oxygen at 25° C., is heated to 100° C., what will be its new volume? This should be done in two steps. First:

$$V_t = V_0(1 + at),$$

$$V_{25^\circ} = V_0 \left(1 + \frac{1}{273} 25 \right),$$

$$72 = V_0 \frac{(298)}{(273)},$$

$$V_0 = 66.$$

Second:

$$V_t = V_0(1 + at),$$

$$V_{100^\circ} = 66 \left(1 + \frac{1}{273} \times 100 \right),$$

$$V_{100^\circ} = 66 \frac{(373)}{(273)},$$

$$V_{100^\circ} = 90.2 \text{ cu.ft.}$$

Problem 13. A sealed vessel contains air at 20° C. and at atmospheric pressure. If it is heated to 1200° C. without change of volume, what would be the resulting pressure?

As in the example above, we will do this in two steps, first:

$$P_{20} = P_0 \left(1 + \frac{1}{273} \times t \right),$$

$$14.7 = P_0 \left(1 + \frac{1}{273} \times 20 \right),$$

$$P_0 = 13.7,$$

$$P_{1200} = 13.7 \left(1 + \frac{1}{273} \times 1200 \right),$$

$$P_{1200} = 74.0 \text{ lbs.}$$

This example may be done in one step by first combining the formulæ as follows:

let t_1 = the initial temperature,

and t_2 = the final temperature,

then $P_{t_1} = P_0(1 + at_1')$,

and $P_{t_2} = P_0(1 + at_2')$.

Transposing

$$P_0 = \frac{P_{t_1}}{1 + at_1} = \frac{P_{t_2}}{1 + at_2}.$$

Substituting

$$\frac{14.7}{1 + \frac{20}{273}} = \frac{P_{1200}}{1 + \frac{1200}{273}},$$

$$P_{1200} = \frac{14.7 \times 273 \times 1473}{293 \times 273} = 74.0 \text{ lbs.}$$

Problem 14. If 200 cu.cms. of hydrogen at 75° F. were cooled to freezing, what volume would result?

$$V_t = V_0(1 + at').$$

Remember that V_0 = pressure at freezing and t' is the difference between the freezing temperature and t .

$$200 = V_{32^\circ} \left(1 + \frac{1}{493} \times 43 \right),$$

$$V_{32^\circ} = 184 \text{ cms.}$$

Problem 15. If 500 c.c. of a perfect gas is taken at atmospheric pressure and 600° F. and cooled to freezing, what volume will it have?

Problem 16. If 500 c.c. of a perfect gas were taken at 300°C . and atmospheric pressure, what would be its pressure at 0°C .?

Problem 17. If 60 cu.ft. of a perfect gas is cooled from a temperature of 100°C . to 20°C ., what will its final volume be?

Problem 18. If a perfect gas were heated from 72°F . and 15 lbs. pressure, to 1600°F ., and if the volume were kept constant, what pressure would result?

34. Absolute Temperature. Inspection of the curve of Figs. 15 and 16 shows an important fact. If projected backward to the X axis they seem to cut it at -273°C . (or at -461°F .). Apparently, if we were to continue to reduce the temperature, the volume in one case and the pressure in the other would be entirely eliminated, and we would have arrived at a state of affairs *beyond which we could not well go*.

If, then, this is the *lowest temperature that could exist*, it is logical to take it as the zero of our temperature scales. Scales using this point as zero are called absolute scales. The absolute centigrade scale uses this point and the centigrade degree, so that temperatures on it are 273° more than on the centigrade scale.

The absolute Fahrenheit scale similarly uses the Fahrenheit degree, and temperatures on it are 461° more than on the Fahrenheit scale. Thus boiling of water takes place at 373° absolute centigrade and at 673° absolute Fahrenheit.

35. Expansion with Three Variables. If the curves of Figs. 15 and 16 were to be replotted, using absolute temperatures, we would have the curve in each case going through the origins. This shows that in the case of expansion at constant volume, the pressure is in direct proportion to the absolute temperature. Also if expansion takes place at constant pressure, the volume is in proportion to the absolute temperature.

If T =absolute temperature, we may express this in symbols thus:

$V \propto T$ where pressure is constant, and V = volume.

$P \propto T$ where V is constant and P = pressure.

or

$$\frac{V}{T} = \text{a constant when } P \text{ is constant.}$$

and

$$\frac{P}{T} = \text{a constant when } V \text{ is constant.}$$

If the data in Figs. 15 and 16 when replotted gave straight-line relations, the following ratios also hold:

$$\frac{V_1}{T_1} = \frac{V_2}{T_2} \quad \text{or} \quad \frac{V_1}{V_2} = \frac{T_1}{T_2},$$

also

$$\frac{P_1}{T_1} = \frac{P_2}{T_2} \quad \text{or} \quad \frac{P_1}{P_2} = \frac{T_1}{T_2}.$$

From these statements it follows that

$$\frac{PV}{T} = \text{a constant,}$$

and

$$\frac{PV}{T} = \frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} = \frac{P_3 V_3}{T_3}, \text{ etc.}$$

The same conclusions may be reached from the following:

From pages 76 and 78 we have:

$$V_{t1} = V_0(1 + \alpha t_1),$$

and

$$V_{t2} = V_0(1 + \alpha t_2).$$

Dividing these two equations,

$$\frac{V_{t1}}{V_{t2}} = \frac{V_0(1 + \alpha t_1)}{V_0(1 + \alpha t_2)}$$

$$= \frac{1 + \alpha t_1}{1 + \alpha t_2}.$$

But in both cases $a = \frac{1}{273}$.

Substituting we have,

$$\frac{V_{t_1}}{V_2} = \frac{1 + \frac{t_1}{273}}{1 + \frac{t_2}{273}} = \frac{\frac{273+t_1}{273}}{\frac{273+t_2}{273}} = \frac{273+t_1}{273+t_2}.$$

But $273+t_1$ = absolute temp. T_1 ,

and

$273+t_2$ = absolute temp. T_2 .

$$\frac{V_{t_1}}{V_{t_2}} = \frac{T_1}{T_2} \quad \text{and} \quad \frac{V_1}{V_2} = \frac{T_1}{T_2} \quad \text{or} \quad V_1 T_2 = V_2 T_1. \quad \dots \quad (I)$$

Similarly,

$$\frac{P_{t_1}}{P_{t_2}} = \frac{P_0(1+at_1)}{P_0(1+at_2)} \quad \text{and} \quad \frac{P_1}{P_2} = \frac{T_1}{T_2} \quad \text{or} \quad P_1 T_2 = P_2 T_1. \quad \dots \quad (II)$$

By Boyle's Law

$$P_1 V_1 = P_2 V_2. \quad \dots \quad (III)$$

If we multiply Eqs. I, II and III together

$$P_1 V_1 V_1 T_2 P_1 T_2 = P_2 V_2 V_2 T_1 P_2 T_1,$$

$$P_1^2 V_1^2 T_2^2 = P_2^2 V_2^2 T_1^2.$$

Taking the square root

$$P_1 V_1 T_2 = P_2 V_2 T_1,$$

or

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}, \quad \dots \quad (1)$$

or

$$\frac{P_1 V_1}{P_2 V_2} = \frac{T_1}{T_2}. \quad \dots \quad (2)$$

By the use of the above formulæ a more simple computation will suffice for the solution of problems like number 12, page 79.

Thus, substituting in (1),

$$\frac{P_1 \times 72}{298} = \frac{P_2 V_2}{373},$$

and remembering that P remains constant,

$$V_2 = \frac{72 \times 373}{298} = 90.2 \text{ cu.ft.}$$

Similarly suppose that 180 cu.ft. of free air at atmospheric pressure, 14.7 lbs. and 70° F. temperature, were pumped into a steel tank of 10 cu.ft. capacity. If the pressure of the air in the tank had in the meantime risen to 300 lbs. per square inch absolute, what must be the temperature of the air in the tank?

Again using formula (1)

$$\frac{14.7 \times 180}{531} = \frac{300 \times 10}{T},$$

$$T = \frac{531 \times 300 \times 10}{14.7 \times 180} = 602^\circ \text{ F. abs.}$$

$$\text{Temp. F.} = 141^\circ.$$

36. Experiments on the Coefficient of Expansion of Air.

A.—RELATION OF V TO T WHERE P IS CONSTANT

Fig. 13 illustrates a piece of apparatus used to determine the coefficient of expansion of air at constant pressure. The U-tube shown has

a closed graduated arm *A*, and into the open arm a glass tube or rod *P* is inserted as a plunger. The bend in the tube is filled with sulphuric acid *S*, which keeps the gas in *A* dry and separates it from the atmosphere. The acid is kept at the same level on both sides by raising or lowering *P*.

The temperature of the air or other gas inclosed in arm *A* is varied by placing the U-tube in a bath consisting of a jar of water or oil.

The following is an extract from the laboratory direction sheets for this experiment.

Experiment H 1-2. Coefficient of Expansion of a Gas at Constant Pressure.

Insert the bend of the tube in the jar and surround it with enough cold water (about 5° C.) to completely cover the short arm. Hang a thermometer in the jar beside the tube. Stir the water frequently, and allow the apparatus to stand until the enclosed gas has had time to take the temperature of the water. Then adjust the plunger in the sulphuric acid until the level of the acid is the same in both arms.

Caution. Do not break the tube or spill any acid upon the person or clothing, as it is concentrated sulphuric acid.

Record the volume of air and the thermometer reading.

Connect to the steam main and pass steam into the heating coil until the temperature of the water has been raised about 10°, and repeat the operations above. Take in this manner a series of readings of temperatures and volumes of gas at approximately equal intervals, until as high a temperature as

practicable (about 80° C.) has been reached. For the higher temperatures, great care should be taken to adjust the levels of acid columns and read the volume just on the instant of reading the thermometer.

From the values obtained, plot a curve showing the change of volume of the gas with temperature, pressure being kept constant. Use temperatures as abscissæ and plot from 0° C. (The bore of the tube being uniform, the length of gas column may be taken as representing its volume.) This curve should be a smooth line so passing

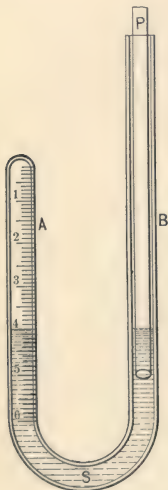


FIG. 17.

between the points as to correct for experimental errors and show probable law of expansion as found.

Extend your curve backward until it cuts the Y axis, thus obtaining volume at 0°C .

Selecting a volume from your curve for some convenient even temperature, preferably as high as possible, compute the apparent coefficient of expansion of the gas at constant pressure from the equation $V_t = V_0(1 + at)$. For V_0 use value obtained by curve.

The absolute coefficient of expansion at constant pressure equals a plus the coefficient of expansion (cubical) of glass.

Using "absolute temperatures" as abscissæ, and starting from "absolute zero" as the origin, re-plot your readings. Continue the curve backward. At what temperature does it cut the X axis?

The curves in Fig. 18 are plotted from a set of data taken from this apparatus.

Substituting in the equations as directed,

$$V_{90.3} = V_0(1 + 90.3a),$$

$$5.25 = 3.94(1 + 90.3a),$$

$$a = \frac{1.31}{90.3 \times 3.94} = \frac{1}{272} = .00368.$$

No correction has been applied for the expansion of glass. Such a correction is hardly necessary, since there are large errors possible in plotting to so small a scale, as well as in reading the volumes, correcting for difference of pressure, etc.

However, such a correction is here made to illustrate the method.

$$\text{Cubical coefficient of glass} = 3 \times .0000087.$$

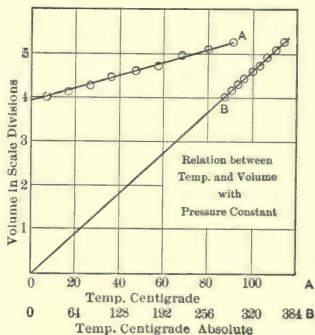


FIG. 18.

The increase per unit volume for 90.3° C. would therefore

$$= 90.3 \times 3 \times .0000087,$$

and for a volume of 5.25 the increase would

$$= 5.25 \times 90.3 \times 3 \times .0000087,$$

$$= .0123.$$

This correction is the largest one to be applied to any of the readings and represents a difference of $\frac{1}{8}$ of the smallest scale division in reading the volume. Clearly it is smaller than the average error in reading the volumes off the tube and in correcting for pressure.

Curve *B* is obtained by replotting the data, using absolute temperature. The curve passes very near the absolute zero.

B.—RELATION OF P TO T WHERE V IS CONSTANT

Fig. 19 is a photograph of a piece of the apparatus used to determine the coefficient of expansion of air at constant volume. It may very properly be called an air thermometer. The air thermometer bulb *A* contains dry air and is mounted upon the same upright frame that is used for the verification of Boyle's law. This upright, *B*, carries a sliding scale, *C*, which is graduated to read directly in pounds per square inch when mercury is used in the adjustable open tube, *D*.

The atmospheric pressure is determined from the reading of the barometer and corrected in the manner explained in the chapter on instruments under "Barometer Corrections." A pointer P_2 (not shown in photograph) is placed on the scale *C* at the corrected value of the atmospheric pressure. This pointer is not moved thereafter, but the whole scale is moved up or down and the pointer P_2 kept exactly opposite *R*, the top of the mercury column in the open tube. P_1 is fixed to *M* and the mercury in the closed side is kept exactly opposite this pointer, while the reading is being taken on the scale *C* at a point directly under the upper edge of *P*.

The following extracts are from the laboratory direction sheets for the use of this apparatus.

Experiment H 1-3. Increase of Pressure of Gas at Constant Volume when the Temperature is Increased.

Hang a thermometer on a hook in the upright support between the mercury columns and place a second marker P_2 on the sliding scale *C*.

Adjust the open tube so that the mercury in the closed tube is opposite the mark M and the marker P_1 , adjust the slider C until pointer P_2 , which must be kept set at the corrected atmospheric pressure, is opposite R , the top of the mercury column in the open tube. Read the pressure in the air thermometer bulb on scale C opposite P_1 . Record this pressure and thermometer reading. Then lower the open arm several millimeters, surround the air bulb with cracked ice and reduce the temperature of the air to 0° . As the gas contracts, its pressure will decrease and the mercury will rise in the stem of the air thermometer. This must be watched carefully and the open arm lowered as contraction occurs, so as to keep the mercury in the stem somewhat below the fixed mark.

Mercury must not be allowed to pass over into the bulb.

When the temperature has fallen to 0°C. , as indicated by the fact that no further changes occur in the position of the mercury column, adjust the open tube and the sliding scale and record the pressure in the bulb and the temperature indicated by the thermometer.

Remove the ice, put on the top, and run a pipe from the steam main to the bottom of the vessel surrounding the air thermometer bulb. See that this is about $\frac{1}{3}$ full of water. Turn on the steam and let it bubble up through the water, thus surrounding the bulb with steam.

Watch the height of mercury in the stem, and raise the vessel of mercury as needed to keep the mercury in the stem about at the

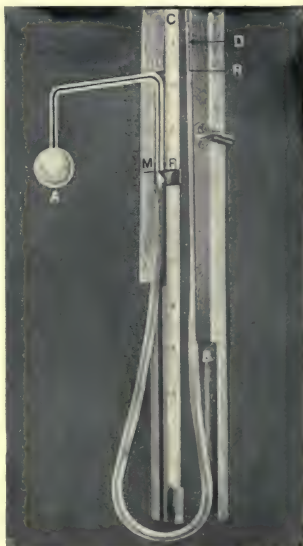


FIG. 19.—Air Thermometer.

mark. When a constant temperature has been reached, set the mercury exactly at the mark, and record as before the pressure of the air in bulb and the temperature on the suspended thermometer outside and also the thermometer in the steam.

N.B. *Lower the open tube before removing the steam jacket.*

Compute the temperature of the steam from the barometer reading.

From your data, compute the *increase of pressure per degree C.* Compare this with the pressure at 0°C . The *ratio of increase of pressure per degree, to pressure at zero* = the coefficient of increase of pressure at constant volume. (The increase in capacity of the bulb is here so slight in comparison with the increase of pressure that it is neglected as being well within the limits of accuracy of the method, and volume of gas is taken as constant when kept at the mark at the stem.)

Express your coefficient both as a fraction having a numerator of one and as a decimal. Assuming the coefficient, from your values of pressure at 0°C ., and room temperature, compute room temperature and compare with thermometer reading. This illustrates a method of measuring temperatures by an air thermometer. With porcelain bulbs high temperatures may be thus measured.

The following data were taken according to these directions.

DATA

Barometer reading.....	14.48 lbs.
" " corrected 748.4 mm.....	14.43 lbs. per sq.in.
1 { Temperature of apparatus.....	23.4° C.
{ Reading of pressure.....	15.42 lbs.
With ice about bulb	
2 { Temperature of apparatus.....	23.2° C.
{ Reading of pressure.....	14.18 lbs.
3 { Temperature of apparatus.....	23.8° C.
{ Reading of pressure.....	19.36 lbs.

COMPUTATIONS

In reading 2, the mercury on both sides was so nearly level that no correction need be made.

In reading 3, the pressure in the bulb differs from that outside by $19.36 - 14.43 = 4.93$ lbs.

Taking the cubical coefficient of expansion of mercury as .000182, the true excess over the atmospheric pressure $P_{99.6}$ is given by the following equations:

$$4.93 = P_{99.6}(1 + 23.8 \times .000182),$$

$$P_{99.6} = 4.91 \text{ lbs.}$$

This result is .02 lb. lower than that obtained without the correction, showing that the pressure as read was .02 lb. too high.

$$\text{True pressure at } 99.6^\circ \text{ C.} = 19.34 \text{ lbs.}$$

$$\text{True expansion from } 0^\circ \text{ C. to } 99.6^\circ \text{ C.} = 19.34 - 14.18 = 5.16.$$

Expansion per degree centigrade, .0518.

$$\frac{\text{Expansion per degree}}{\text{Pressure at } 0^\circ \text{ C.}} = \frac{1}{274} = .00366.$$

From these experiments it will be seen that the coefficient of expansion at constant volume may be found by noting the increase in pressure between any two temperatures and dividing this by the increase in temperature and by the computed pressure at 0° C. The coefficient of expansion at constant pressure may be found similarly. By this method the coefficient of expansion of gases, which would condense to the liquid state or even become solid if cooled to zero, centigrade, are found and referred to standard conditions. However, the coefficient of expansion so determined is not constant for any given gas, and its value will depend upon the range of temperatures over which it has been determined. This temperature range should always be stated with the coefficient, for the coefficient to have any accurate meaning.

The coefficient of expansion of a gas as just defined applies only to a so-called perfect gas; that is, a gas that obeys Boyle's and Charles' laws. Since there is no gas that obeys these laws we must not expect the coefficients to be exactly equal to the theoretical value given. In the case of any particular gas the coefficient of expansion at constant pressure, and the coefficient of expansion at constant volume will both differ from the theoretical value and from one another.

By assuming that you know the constants of the apparatus used in Experiment 31-3, the piece may be used as a thermometer. A refined type of this thermometer, known as the standard air (hydrogen and nitrogen have also been used) thermometer, is regularly used to calibrate and correct very accurate mercury thermometers.

37. Expansion of Gases. Boyle's and Charles' laws. In Section 35, Boyle's and Charles' laws were combined in the following formulæ:

$$\frac{PV}{T} = \text{constant, and } \frac{PV}{T} = \frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} = \text{etc.,}$$

where **P** is pressure, **V** is volume, and **T** is absolute temperature.

"**R**" is often used for this constant when the formula is applied to one pound of air, and the formula is then written:

$$PV = RT.$$

Since 1 lb. of air at 14.7 lbs. per sq.in. pressure occupies about 12.4 cu.ft. at 32° F. or 493° absolute Fahrenheit, for air, when **P**, **V**, and **T** are in this set of units.

$$R = \frac{14.7 \times 12.4}{493} = .37.$$

For any weight of air in pounds the formula is:

$$\frac{PV}{T} = .37W.$$

This formula is very frequently used with the value .37 for mixtures of gases other than air. In gas-engine problems, for example, **R** = .37 gives results as accurate as the nature of the problems requires.

Sometimes **P** is expressed in lbs. per sq.ft., in which case the pressure is numerically 144 times larger and **R** = .37 × 144 = 53. See section 68, Chapter VIII.

By using this expression, one may briefly and quickly solve many practical problems which would require many steps if worked by the formulæ containing the coefficient of expansion. One cannot investigate in a quantitative way what takes place in the cylinder of an air compressor, of an explosion engine, or of a steam engine without its use.

A few simple problems will be given here in advance of the chapters on "Steam Power Plants," and "Gas Power Plants," to illustrate the use of the above formulæ.

In order to express these problems in the usual technical language the following terms are used:

THE **STROKE** of an engine is the linear distance along the cylinder swept through by the piston.

That part of the total volume at each end of the cylinder not swept through by the piston is called the **CLEARANCE**. Clearance is necessary for several practical reasons, one of which is to prevent pounding due to the compression of any small amount of liquid and of the usual amount of gases left in the cylinder after exhaust takes place. Clearance is expressed in per cent as the ratio of the volume not swept through by piston to the volume swept through by piston.

The **BORE** of an engine is the diameter of its cylinder.

Problem 19. An air compressor pumps 100 cu.ft. of free air per minute from a room of average temperature of 78° F. What is the weight of air pumped? (Neglect effect of moisture.)

14.7 normal atmospheric pressure.

$$V = 100 \text{ cu.ft.},$$

$$T = 461 + 78 = 539,$$

$$\frac{PV}{T} = \frac{14.7 \times 100}{539} = .37W,$$

$$W = \frac{14.7 \times 100}{539 \times .37} = 7.4 \text{ lbs.}$$

Problem 20. The air in Problem 19 is conveyed to a rock drill at 100 lbs. per square inch pressure, and before being used is

preheated to 400° F. What volume of compressed air is used by the rock drill?

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2},$$

$$\frac{14.7 \times 100}{539} = \frac{100 V_2}{861},$$

$$V_2 = 20.0 \text{ cu.ft.}$$

Problem 21. A gas engine having 20 per cent clearance draws a charge at 14.7 lbs. pressure and 70° F. If, when the charge is compressed into the clearance, the abs. pressure is 160 lbs., what is the temperature? Assume that the charge fills both the clearance and the volume displaced by the piston.

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2},$$

$V_1 = 120$ per cent of the stroke $\times$ piston area, since gas is drawn into both the clearance volume and the volume displaced by the piston as it makes its stroke.

$V_2 = 20$ per cent of the stroke $\times$ piston area, as the piston compresses all the gases into the clearance volume, which is stated to be 20 per cent.

$$P_1 = 14.7,$$

$$P_2 = 160,$$

$$T_1 = 461 + 70 = 531.$$

Then

$$\frac{14.7 \times 120}{531} = \frac{160 \times 20}{T_2},$$

$$T_2 = \frac{160 \times 20 \times 531}{14.7 \times 120},$$

$$T_2 = 963 \text{ absolute,}$$

or

$$502^{\circ} \text{ F.}$$

Problem 22. In Problem 21, after the charge is fired the temperature becomes 3258°F . What was pressure then?

If we assume that the piston has not moved from its position, in the previous problem the volume remains the same as before and so $V_2 = V_3$.

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} = \frac{P_3 V_3}{T_3},$$

$$\frac{14.7 \times 120}{531} = \frac{P_3 20}{3719},$$

$$P_3 = 560.7 \text{ lbs. absolute,}$$

or, 546 lbs. per square inch in excess of atmosphere.

Problem 23. In Problem 21, at the end of the expansion stroke, the pressure becomes 40 lbs. What was the temperature?

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} = \frac{P_3 V_3}{T_3} = \frac{P_4 V_4}{T_4},$$

$$\frac{14.7 \times 120}{531} = \frac{40 \times 120}{T_4},$$

$$T_4 = 1445 \text{ absolute,}$$

or 984°F .

Problem 24. 1000 cu.ft. of free air at 72°F . weighs how much?

Problem 25. If compressed to 120 lbs. per square inch, and cooled to 72°F ., what volume would the air in Problem 24 occupy?

Problem 26. At a temperature of 500°F ., what volume would it occupy if under 120 lbs. pressure?

Problem 27. An automobile tire is pumped up to 80 lbs. per square inch at a temperature of 80°F . If it would burst at 100 lbs. pressure, how hot must it get before bursting? Assume that the volume of air in the tube does not change.

Problem 28. Solid CO_2 gives a temperature of -80°C . If a glass bulb were sealed off while it was cooled to this temperature, what pressure would result inside the bulb if it contained air and was heated to a room temperature of 25°C . Assume that no change in volume takes place in the bulb.

Problem 29. If this glass bulb has a volume of 1000 c.c. at 25°C ., what weight of air does it contain?

Problem 30. What is R for 1 lb. of CO_2 in the expression $PV = RT$ if under standard conditions 1 cu.ft. of CO_2 weighs .07704 lb.?

Problem 31. A gas engine having 25 per cent clearance draws a charge at 14.7 lbs. pressure and 60° F. If when the charge is compressed into the clearance the pressure is 141.1 lbs., what is the temperature?

Problem 32. In Problem 31 after the charge is fired the temperature becomes 4258° F. What was pressure then?

Problem 33. In Problem 31, at end of expansion stroke, the pressure becomes 69.4 lbs. What was the temperature?

Problem 34. A charge of .033 lb. of gas and air was drawn into a cylinder having .8 in. clearance, 8.8 ins. stroke, and 10 ins. diameter. Combustion temperature = 4000° F. After expansion, temperature was reduced to 2000° F.

What was pressure at explosion?

What was pressure at end of expansion?

38. Density and Volume Affected by Expansion. A solid cube of a given material, having unit dimensions at 0° C., may have a density as given in the table for such a substance, but clearly if it is heated to t° C., its volume will have changed though its weight will remain the same. If its original weight at 0° C. = W_0 and its volume = 1, its new volume will be $1 + 3at$ when a is its linear coefficient of expansion.

As W_0 is really the weight per unit volume or the density at 0° C., the density at t° C. will be different. If W_T equals the density at T° C., we may write its value as,

$$W_T = \frac{W_0}{1 + 3at}$$

a quantity which is clearly smaller than W_0 when a and T are positive.

Tables of densities of materials should accordingly be used with care when the materials are at a temperature varying considerably from the normal, or from that at which the densities were determined. The correct density may be obtained by first finding the change in volume that would take place during the change of temperature from that mentioned in

the table to the temperature found in actual practice. The corrected density will equal the old density divided by one plus the change in volume. For an illustration of such a computation see the set of problems following this section.

Liquids vary in density more than solids, and seldom is this variation in direct proportion to the temperature. Water, for example, as it is heated from the freezing-point, first has a negative value for its coefficient of expansion until about 4° C. is reached, when the coefficient changes to a positive value. This really means that water contracts in warming from 0° C. to 4° C., and consequently has a maximum density at 4° C. When the temperature varies in either direction from 4° C., expansion takes place.

The density of gases varies from an infinitely small quantity to a value greater than the same substance normally has when in the liquid state.

From Section 37 it follows that the weight is in proportion to $\frac{PV}{T}$ and the density, or weight per unit volume will vary as the weight divided by the volume, or

$$W \propto \frac{PV}{T}, \quad (1)$$

then

$$\frac{W}{V} \propto \frac{PV}{TV} \quad \text{or as} \quad \frac{P}{T}. \quad (2)$$

Then for gases if D_0 is the standard density and D_T is the density at T degrees:

$$\frac{D_0}{D_T} = \frac{\frac{P_0 V_0}{T_0}}{\frac{P_2 V_2}{T_2}}.$$

$$\frac{D_0}{D_T} = \frac{\frac{P_0}{T_0}}{\frac{P_2}{T_2}}.$$

The density of gas varies from a value greater than the same substance has when in the liquid state to an infinitely small quantity.

Problem 34A. What is the density of the products of combustion of a furnace as they go up an 80-ft. chimney at 600° F.? Assume that they weigh and act like air.

Assume 1 cu.ft. of air under standard conditions weighs .0817 lb.

Let D_T = the density at 600° F.

$$\frac{.0817}{D_T} = \frac{\frac{14.7}{493}}{\frac{14.7}{1061}} = \frac{14.7}{493} \times \frac{1061}{14.7} = \frac{1061}{493},$$

$$D_T = \frac{.0817 \times 493}{1061} = .0380.$$

Problem 35. If the air outside of the chimney in the above problem is at 82° F., what is the density of the air inside and what is the difference in pressure between the outside and the inside of the base of the chimney?

$$\frac{.0817}{D_T} = \frac{\frac{P}{493}}{\frac{P}{543}}, \quad D_T = .0742.$$

The difference in density is therefore $.0742 - .0380 = .0362$ lb.

One foot height produces therefore a difference of pressure of .0362 lb. per square foot or $\frac{.0362}{144}$ lb. per square inch; 80 ft. height

would produce $\frac{.0362 \times 80}{144} = .0201$ lb. per square inch.

This corresponds to a draft of $\frac{.020}{.036}$ inch of water.

Problem 36. If copper weighs .320 lb. per cubic inch at 24° C. and has a mean linear coefficient of expansion of .0000168, what would its density be at 364° C.?

$$W_T = \frac{.320}{1 + .0000168 \times 340 \times 3},$$

$$W_T = .314 \text{ lb. per cubic inch.}$$

REVIEW PROBLEMS, CHAPTER IV

37. If the products of combustion of a gas engine have the same density as air and leave the cylinder at 800°F ., find their density. What was the weight of the gases in the cylinder if it had an 8-in. bore and a 10-in. stroke?

39. If a 120-ft. chimney has a temperature inside of 300°C . and outside it is 20°C ., what would a draft gauge at the base read in inches of water and in lbs. per sq.in.?

40. If lead weighs .410 lb. per cubic inch at 60°F ., what would it weigh at 300°F .?

41. What change takes place in an iron tire whose diameter is 4 ft. at a temperature of 400°F ., when cooled to 70°F .?

42. An iron bridge is 300 yds. long. Find play that must be allowed for a range in temperature from -10°F . to 120°F .

43. The end of an iron boiler is a circle 3 ft. in diameter at 35°F . What is the area change when heated to 212°F .?

44. A steel drum 40 ins. in diameter is to have shrunk upon it a steel collar. The shop temperature is 60°F . and the collar is to be heated to 620°F . To what diameter should the collar be turned at shop temperature if it is to have a diameter of 40.050 when hot?

45. With what force does a steel rail of 8 sq.in. cross-section tend to expand when heated from 40°F . to 100°F .? (Modulus of elasticity of steel = 30,000,000.)

46. A boiler tube has 1.2 sq.in. cross-section of steel. Cold water at 120°F . and steam at 200 lbs. pressure pass alternately through this pipe. With what force does it tend to expand lengthwise?

47. A steam main of wrought-iron pipe having a 4 sq.in. metal cross-section is piped from a boiler to an elbow which is hard against a brick wall. With what force will the boiler be pushed away from the wall if piping was done at 22°C ., and steam is passed through the pipe at 120°C .? (Modulus of elasticity 30,000,000.)

48. A quantity of oxygen occupies 500 cu.cms. at 20°C ., and 950 mms. abs. pressure. At what temperature would abs. pressure be 540 mms., if the gas were allowed to expand to 600 cu.cms.?

49. A quantity of air occupies 10 cu.ft. at 0°C . and 15 lbs. pressure. What pressure will it exert if the volume is decreased to 5 cu.ft., and the temperature to -150°C .?

50. What would be the effect of placing a brass tube in a steel boiler shell and making both ends of the tube fast? Compute amount of effect for a 16-ft. length of tube.

SUMMARY, CHAPTER IV

The COEFFICIENT OF LINEAR EXPANSION of a solid defines the rate of increase of length due to a rise of temperature. Numerically it is obtained by dividing the increase in length by the original length and by the increase in temperature.

For the **COEFFICIENT OF EXPANSION OF AN AREA**, twice the linear coefficient may be used, if the body expands at a uniform rate along all axes.

THE COEFFICIENT OF CUBICAL EXPANSION, under similar circumstances, may be taken as three times the linear coefficient.

Tables usually give only the linear coefficient of expansion for solids, and the cubical coefficient for fluids.

The APPARENT COEFFICIENT OF EXPANSION of a liquid is smaller than the true coefficient by the amount of the expansion of the containing vessel.

The EXPANSION OF A PERFECT GAS obeys the following laws providing that the temperatures are high above the critical point:

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} = \frac{P_3 V_3}{T_3} = \text{etc.}$$

This means that:

P varies as $\frac{1}{V}$ when the **T** is constant.

P varies as absolute **T** (Boyle's Law) when the **V** is constant.

V varies as absolute **T** when the **P** is constant.

If **T** varies as the total heat energy (Charles' Law) in a body, and if all heat energy were taken away, **P**, **V**, and **T** would all be zero. From the rate of expansion at normal temperatures, we find that we would reach such a point at approximately -273°C . and so this point is used as the **Absolute Zero**, or the zero point of the absolute, centigrade scale. Zero on the absolute Fahrenheit scale is -461°F .

The **DENSITY** of any body varies with its **T**, **P**, and **V**, when the body expands. Density should be given for a definite temperature only, and corrected when applied to bodies at other temperatures.

CHAPTER V

THREE STATES OF MATTER

39. All Elements Have Three States. When an element is mentioned we usually form a definite mental picture of the substance with definite physical and chemical properties. Thus we think of iron as a hard gray solid, heavier than aluminium but not so heavy as lead, etc. Yet we are all aware of the change in its ductility that takes place at about "red heat," above which temperature it is easily hammered into any desired shape. We know that it can be melted in a cupola and made a liquid. Upon reflection it is not strange that all of its properties should be undergoing greater or less change as its temperature rises. Age and use may make great changes in properties such as its magnetism and tensile strength, even though the temperature of a substance remain unaltered. *Any solid element* may be made a liquid or a gas if heat intense enough is supplied to reach the required temperature. On the other hand *any gas* may be changed to a liquid or to a solid provided energy enough is taken from the gas to reduce its temperature sufficiently.

Frequently solid compounds cannot be changed to liquids by the application of heat because of their tendency to decompose. Wood or pure cellulose, for example, when heated never becomes liquid, but is broken up into various volatile compounds, and solid carbon or charcoal. It would be a very handy thing if we could melt and cast wood.

Similarly many liquids cannot well be changed to gases without their changing in chemical composition. Lard, for example, is easily melted to a liquid and is thus commonly

used. But if liquid lard is heated too hot it decomposes, giving off gases which do not smell well and leaving behind in the vessel a porous mass of carbon. Sulphuric acid and nitric acid are other illustrations of substances which change in character as they are heated in air.

Increasing the energy in any substance or mixture of substances always tends to make chemical changes easier. When the chemist mixes liquid or solid substances in which he expects to produce some chemical action, if this action does not go on as fast as desired, his first thought is to heat the mixture. This practice is so common that with the chemist it is taken as a matter of course.

There is no single substance with which we more frequently come in contact than water. In the following section, the changes that take place in water are more fully discussed as an illustration of the kind of changes that take place in all substances. *The student should not think that any of these changes are peculiar to water. The numerical values given, however, do not apply to any other substance.*

40. Ice, Water and Steam. It has already been stated that one B.T.U. of heat energy delivered to 1 lb. of pure ice at 0° F., under standard conditions of pressure, will cause its temperature to rise about 2° F., since the specific heat of ice is about .504. Approximately 16.1 B.T.U. will heat a pound of ice from 0° F. to 32° F. At this point if more heat energy is added the temperature of the ice does not increase, but the ice begins to melt. The temperature of the resulting mixture of ice and water will remain at 32° F. until enough heat energy has been delivered to it to melt all of the ice. This takes between 143 and 144 B.T.U. After the ice has all melted, then there will be a rise of approximately 1° F. for each B.T.U. added until the water reaches 212° F., when the water begins to boil. The temperature of the water will not increase above 212° F. after boiling begins until it is all boiled away, although in the

meantime 970 B.T.U. per lb. must be supplied. For each .50 B.T.U. supplied to this pound of steam, there will be thereafter a rise in temperature of approximately 1° F.

The two succeeding figures are intended to graphically illustrate this change.

In Fig. 20, the curve OA was plotted on the assumption that the specific heat of ice equals .50 and is constant below

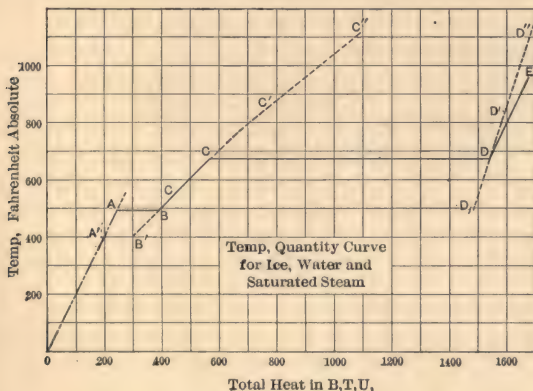


FIG. 20.

freezing. (Of course the specific heat for the entire range cannot be determined, as we cannot reach absolute zero.)

AB shows the energy required to change 1 lb. of ice to water.

BC shows the energy required to raise the pound of water to the boiling-point at atmospheric pressure.

CD shows the energy to vaporize the water at atmospheric pressure.

DD'' represents the energy needed to heat the pound of steam to 1100° F. absolute, and keep it saturated under pressure.

DE is the curve that would result if the steam had been superheated at atmospheric pressure. (See page 133 and Table XI.)

In general we are not interested in the energy contained in ice below 0°F ., and accordingly Fig. 21 shows the total energy per pound for various temperatures and pressures above 0°F .

$A'A_1$, $B'C''$, D_1D'' , D_1E_1 , DE , and $D'E'$, are not straight lines because the specific heat of the ice, water, and steam is not a constant.

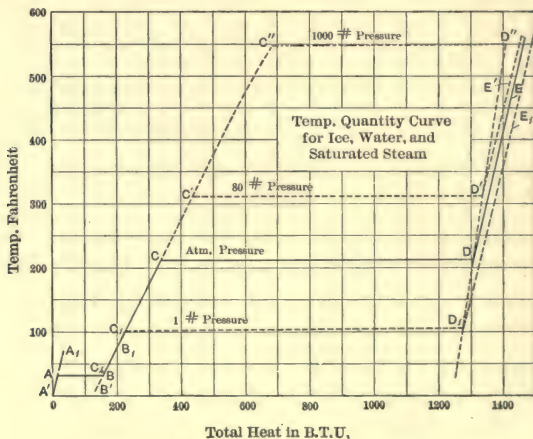


FIG. 21.

41. Latent Heat. The heat energy necessary to change a unit mass of a substance from the solid to the liquid state without change of temperature is known as its *Latent Heat of Fusion*, or *Latent Heat of Melting*.

It requires 144 B.T.U. to change ice to water without change of temperature, therefore we may call the "latent

heat of fusion" of ice or the "latent heat of melting of ice," 144. It is termed "latent" (i.e., hidden) because these B.T.U.'s of heat energy do not produce any increase in temperature of the ice or water and so do not have any effect upon a thermometer in the mixture.

In the metric system, the latent heat of fusion, is $\frac{5}{9}$ of 144, or 80.

Similarly, the **Latent Heat of Vaporization** is the heat energy necessary to change a liquid to the gaseous state without change of temperature. To change water under standard conditions of pressure to steam at the same temperature and pressure requires 970 B.T.U. per lb., or $970 \text{ B.T.U.} \times \frac{5}{9} = 539$ calories per gr.

To change water from 32° F. into steam at 212° F. has taken $180 \text{ B.T.U.} + 970 \text{ B.T.U.}$ or 1150. This is called the total heat of steam at 212° F. The value of the latent heat of vaporization is decreased by increasing the pressure. The temperature at which boiling and freezing takes place is also altered by the pressure.

Thus if we take water at 32° F. under an absolute pressure of 1 lb. per sq.in. and add 70 B.T.U. of heat energy to it, the temperature will reach 102° F. It will here begin to boil and require 1035 B.T.U. to convert it all to steam.

$70 \text{ B.T.U.} + 1035 \text{ B.T.U.} = 1105 \text{ B.T.U.}$, the total heat of steam at 102° F.

If, however, we take 1 lb. at 80 lbs. per square inch and 32° F. , we must add 282 B.T.U. to raise it 312° F. before it begins to boil, but it takes only 900 B.T.U. to change it all into steam.

$282 \text{ B.T.U.} + 900 \text{ B.T.U.} = 1182 \text{ B.T.U.}$, total heat of steam at 312° F.

In Fig. 21 these facts are shown in graphical form. The solid lines show the result of adding energy to the substance at atmospheric pressure 14.7 lbs. per sq.in.

CD is, accordingly, the normal latent heat of vaporization and **AB** the latent heat of fusion.

C₁D₁ is the latent heat of vaporization at 1 lb. pressure.

C'D' is the latent heat of vaporization at 80 lbs. pressure.

C''D'' is the latent heat of vaporization at 1000 lbs. pressure.

It will be noticed that these lines are not equal in length, showing that the latent heat of water in B.T.U. depends upon the pressure under which boiling takes place. The latent heat *tends to* decrease as the pressure increases. Its amount at any temperature can always be found by measuring the horizontal distance between the lines **C₁C''** and **D₁D''** at a height above the **X** axis that represents the given temperature.

The effect of pressure upon the latent heat of fusion is much less, and practically can be neglected, as pressure only slightly affects the freezing-point. It is a peculiar fact that pressure lowers the freezing-point, though we have just noticed that it raises the boiling-point. The amount of the latent heat at temperatures other than 32° F. can be taken from the curve just as for vaporization.

In Fig. 21 there are illustrated three different ways of obtaining saturated steam at 80 lbs. pressure, the condition represented by the point **D'**. If pure water under 1 lb. (absolute) pressure is heated from a temperature of 32° F. to the boiling-point at this pressure, 102° F., 70 B.T.U. must be added. The temperature will not rise further (unless the water contains salts) until the latent heat, 1034 B.T.U., is added to change the water into steam. The steam may then have its temperature increased to 312° F. by being mechanically compressed and by allowing 78 B.T.U., of the work done upon it during compression to remain in the steam as heat energy. The pound of steam will then contain a total energy above water at zero degrees Fahrenheit of 1182 B. T.U.

If we start with water at 32° F. and atmospheric pres-

sure, we have just seen that $180+970$ or 1150 B.T.U. must be added to change the water to steam. To change the steam at atmospheric pressure to saturated steam at 80 lbs. pressure would require the addition of 32 B.T.U. of mechanical work. In this process the heat added in each step was different in amount from that added during each corresponding step in the previous case and yet the total energy added to form the saturated steam at 80 lbs. proves to be 1182 B.T.U., no matter what steps are used to bring the steam to condition D' .

If there is salt in the water the only effect will be to raise the boiling-point before evaporation actually begins and during evaporation as well. The addition of a small quantity of salt would cause the line C_1D_1 and $C''D''$, etc., to be out of parallel with the X axis. See Fig. 21, in which the effect is shown for the lines mentioned.

The curve BCC'' is not a straight line, but is rapidly bending at C'' . The curve D_1DD'' for saturated steam goes up almost parallel with the Y axis after crossing the 1400 line. These two lines intersect a little above 675° F. This is the critical temperature (see definition page 114) of steam and theoretically we should have no liquid existing above that temperature. If we could actually see what happens during the process of heating water at 3000 lbs. pressure we would find that the meniscus disappears at about 675° F., but if we place a suitable colored salt in solution while we continue to increase the temperature we would probably find that the volume below the meniscus would still remain colored after the critical temperature had been passed and would persist for several degrees above the critical temperature. At the point at which these two curves intersect the latent heat disappears. Probably this effect as well as all of the others which characterize the critical temperature cannot be said to take place at a definite temperature, but between two such temperatures as 670° F. and 700° F. At this critical temperature the liquid loses

the cohesion between its molecules which characterizes the liquid state. The density of the liquid and the gas is the same at the critical temperature. If the liquid is said to persist for a small rise of temperature above the critical temperature it is on the assumption that the two mix by diffusion.

(Assume specific heat to be the same as in the tables unless given.)

Problem 1. How many B.T.U. will be required to raise 10 lbs. of lead to the melting-point and melt it from a temperature of 60° F.?

Heat to raise 1 lb. to M.P. = $(621 - 60).0315 = 17.7$,

Heat to raise 10 lbs. to M.P. = $17.7 \times 10 = 177$,

L.H. of lead = 9.7 B.T.U.,

Heat to melt 10 lbs. = 97 B.T.U.,

Total heat required = $177 + 97 = 274$ B.T.U.

Problem 2. How many pounds of steam at atmospheric pressure will be required to raise a ton of boiler-feed water to 200° F. from a temperature of 60° F., if the steam is condensed into the water?

1 lb. of steam has 970 B.T.U. latent heat and in cooling from 212° to 200° gives up 12 B.T.U. Total heat given up per pound therefore equals

$$970 + 12 = 982 \text{ B.T.U. per lb.}$$

Each pound of cold water is heated, $200 - 60 = 140^\circ$, and therefore requires 140 B.T.U. Total heat required = $140 \times 2000 = 280,000$ B.T.U.

$$\text{Steam required} = \frac{280000}{982} = 285 \text{ lbs.}$$

Problem 3. A hot piece of steel weighing 18 lbs. is quenched in 15 lbs. of water originally at 52° F. If $1\frac{1}{2}$ lbs. of the water boiled away, what was the temperature of the steel? Assume the specific heat for this range to be .12.

Heat gained = heat lost.

15 lbs. of water heated to 212 from 62 require $15 \times (212 - 52)$ or 2400 B.T.U.

1.5 lbs. of water changed to steam at atmospheric pressure require $970 \times 1.5 = 1455$ B.T.U.

Total heat gained by water $= 2400 + 1455 = 3855$ B.T.U.

If T represents the initial temperature of the steam, and .12 is the mean specific heat, then the heat lost by the steel $= 18 \times .12(T - 212)$.

$$3855 = 18 \times .12(T - 212).$$

$$T = \frac{3855}{2.16} + 212 = 1997^\circ \text{F.}$$

Problem 4. How many B.T.U. will be required to melt 30 lbs. of zinc from a temperature of 72°F. ?

Problem 5. Ice is used to cool a Prony brake which is absorbing 10 H.P. How much ice is required per hour if the water escapes at 60°F. and the ice is at 28°F. when used?

Problem 6. A calorimeter contains 60 gms. of water and has a water equivalent of 80 gms. Its temperature is 20°C. 200 gms. of ice and 45 gms. of steam under standard pressure are added. Find the resulting temperature.

Problem 7. How many pounds of water can be evaporated from water at 212°F. to steam at 212°F. (usually more briefly written "pounds of water from and at 212°F. ") from 1 lb. of coal containing 14,000 B.T.U., if no heat is lost?

42. Definitions and Distinctions. The following statements are familiar, but they will be repeated here for ready reference.

The characteristic which we use in defining a solid is its relative permanence of shape and volume. If pressure is applied to a solid like rubber we see it yield and when the pressure is released it returns to its original shape, if the pressure has not been so great as to strain the material beyond its elastic limit. We therefore say:

Solids have elasticity *both* of shape and of volume.

Liquids have no characteristic shape, but will take the shape of the containing vessel. Their volume under a given temp. and pressure is definite. With a given liquid, if we increase the pressure and temperature, its volume will increase proportionately, and if the pressure and temperature

are restored to their original values the volume of the liquid will also return to its original value. Therefore it is generally true that:

Liquids have *no* elasticity of shape, but perfect elasticity of volume.

Even the volume of a given weight of gas is uncertain. It depends upon both the pressure and the temperature. Accordingly we say:

Gases have elasticity of *neither* shape nor volume.

Fog consists of small particles of liquid floating in a gas (most commonly in air).

Vapor is a word commonly used in speaking of a gas at a temperature near that at which the liquid state of the same substance can exist. Sometimes it is loosely used to mean a mixture of fog and gas of the same substance or even to refer to fog. Vapor is *not* a good *technical* term.

Saturation. A gas is said to be *saturated* (or a vapor is said to be saturated) when its weight per unit volume is the lowest attainable at the given temperature and pressure and when it is still in contact with its liquid phase. Saturated gases are usually found in contact with their liquid state. If heat energy is taken from the gas and the pressure kept constant, some of the gas will be changed to liquid, but the weight per unit volume of the gas will remain the same.

The student often asks if a saturated vapor is wet. There are frequent cases where this term is used in the following manner: The speaker knows that the steam which he is using in his engine is not superheated (as will be seen later superheated steam contains no moisture). He says it is saturated without considering whether there is any fog in the steam. Therefore, to be definite many speak of dry saturated steam when they wish to indicate a quality of steam which when passing through a perfect steam separator would lose no liquid. However, the term saturated steam should be sufficient to express this idea.

Saturated steam to the eye looks like air or any other gas. It is colorless and transparent. When in winter steam blows

into the air and looks white, it is fog that we see and not steam. If the student will notice the exhaust from a locomotive stack he will generally see a zone immediately above in which only the smoke may be seen. Further up he will see a cloud of white. This is the fog, or in other words, small drops of water carried up by the flue gases.

A given weight of gas at a given temperature, is said to be saturated when it exerts the maximum pressure and has the greatest possible volume at that temperature. If the student will study Table IX he will see that this definition excludes both *wet* and *superheated* steam. The values given in Table IX apply only to *saturated* steam.

If heat energy is taken away in large enough quantity the gas may all be changed to liquid, but the temperature will not change, unless the pressure changes, until all of the gas has been converted into liquid. Then if the process of taking away heat energy is continued, the liquid will be cooled below the temperature which it had while in the gaseous state.

If, on the other hand, the temperature is kept constant by immersing the vessel containing the gas and liquid in a bath, any attempt to increase the pressure by decreasing the volume will merely result in more liquid being formed. In that event the weight of the gas per unit volume will remain constant.

If the mass of saturated gas just referred to is led away from contact with liquid and while the pressure is kept constant more heat energy added, the temperature of the gas may be raised or the volume may be increased or perhaps both temperature and volume may be increased. Under any of these conditions the weight per unit volume is less than that of saturated gas at the same pressure, and the gas is said to be **superheated**.

Quality. When we draw steam from a boiler it may contain fog, or as is sometimes said, entrained water. A

factor called the quality of steam is used to express its per cent of dryness. When a number like 97.8 is used we mean that 97.8 per cent of the mixture is gas. If steam is superheated the quality is defined by the number of degrees of superheat. In Table X this practice is followed.

The process of changing a solid to the liquid state is called **melting**.

The reverse process is called **freezing**.

The process of changing a liquid to the gaseous state is called **vaporization**. The reverse process is called **condensation**.

Boiling is rapid vaporization, characterized by the formation of bubbles in the liquid, which rapidly rise to the top.

Evaporation is frequently used to mean slow vaporization without boiling.

The **melting-point** of a substance is the temperature at a given pressure at which the solid and liquid states can exist together as a mixture in thermal equilibrium.

The **freezing-point** is usually the same as the *melting-point*.

When a solid goes direct from the solid to the gaseous state, it is said to *sublime*.

When two pieces of a solid, near its melting-point, like ice, for example, are pressed together under large pressure and then released they are usually found to have frozen together. The process is called *regelation*.

The **boiling-point** of a substance in the liquid state at a given pressure is the temperature of saturated gas of that substance at that pressure.

We usually talk of the boiling-point of a liquid as being a rather definite temperature, but a number of common experiences teaches us that it is unsafe to define the boiling-point as the temperature at which boiling takes place. It is well known that if pure substances are used, they may with care be heated while under atmospheric pressure

far above their normal boiling-point without rapid evaporation taking place. Then suddenly something may start a bubble and almost all the liquid may be thrown out of the vessel by the rapid boiling that will then take place and continue until the liquid is cooled down to its normal boiling-point again.

The boiling-point of a liquid is always dependent upon the pressure upon it. Unless otherwise stated, it is always assumed that a boiling-point mentioned for a given liquid is for atmospheric pressure.

The presence of even small quantities of solid impurities may change the temperature of a boiling liquid from its true boiling-point; but the gas developed will have a temperature dependent only upon the pressure upon it during formation.

The freezing-point of a substance is also greatly affected by the presence of impurities.

Frequently a determination of the temperature at which boiling or freezing takes place is resorted to in order to find out the purity of the liquid in question. For a further discussion see Cryogenics in Chapter X.

Air, indoors or out, always contains a considerable amount of water in the gaseous form. The ratio, expressed in per cent, obtained by dividing the weight per unit volume of water vapor in air at a given temperature by the maximum weight that could exist in air at that temperature, is its **relative humidity**.

The maximum pressure that water can exert at any temperature is called its **vapor tension** for that temperature.

The **dew point** is the temperature to which the atmosphere must be cooled to have the water contained in it in gaseous form become saturated. During a warm day the air frequently takes up a large amount of water vapor. In that event the vapor tension rises, though the relative humidity may become either higher or lower according to the relative rate of increase of the temperature and

the vapor tension. As soon as the air begins to cool, the relative humidity rises until it is 100 per cent, when the dew point is reached. The vapor being then saturated, condensation takes place as cooling continues, and the water condensed is called **dew**.

There is a temperature for each element and compound above which it cannot exist as a liquid. This temperature is known as the **critical temperature**. Above the critical temperature no amount of pressure will liquefy the substance. The pressure of the dry saturated vapor at the critical temperature is called the **critical pressure**. This is the minimum pressure at which a liquid state is possible at this temperature. The numerical value of the critical temperature and of the critical pressure defines the condition of a substance when it is in the critical state.

To illustrate: If we want to change air to liquid air at the highest possible temperature we must first apply an absolute pressure of 585 lbs. per square inch and then while maintaining this pressure cool it to a temperature slightly below its critical temperature, namely -220° F. No amount of increase in pressure will avail in producing liquid if the cooling temperature rises above -220° F. If temperatures lower than -220° F. are used, a less amount of pressure than 585 lbs. per square inch is required.

43. Dalton's Law. Suppose a chamber has a volume of 10 cu.ft. and that it is filled with a perfect gas (*c*) under 4 lbs. pressure. If we compress this gas into 2 cu.ft. at constant temperature, we would obtain the resulting pressure by Boyle's law as follows:

$$V_c P_c = V_1 P_1 \quad \text{or} \quad 10 \times 4 = 2 P_1 \quad \text{and} \quad P_1 = 20. \quad . \quad (1)$$

Similarly, if the chamber were filled with a second perfect gas (*d*) until its pressure were 16 lbs. and the volume reduced to 8 cu.ft., we would find:

$$V_d P_d = V_2 P_2 \quad \text{or} \quad 10 \times 16 = 8 P_2 \quad \text{and} \quad P_2 = 20. \quad . \quad (2)$$

Now suppose this chamber to be separated by a perfectly flexible diaphragm into two parts and on one side is placed the quantity of gas (*c*) which satisfied Eq. (1) and on the other side is placed the quantity of gas (*d*) which satisfied Eq. (2). The resulting pressure on both sides of the diaphragm must be equal, and by Boyle's law it follows that the volumes are 2 cu.ft. and 8 cu.ft. respectively and the equal pressures must be 20 lbs. per square inch.

Now if the diaphragm were ruptured the gases would diffuse and form a mixture of the same general nature as the mixture of oxygen and nitrogen in the air. The gas (*c*) would then be uniformly distributed through the whole 10 cu.ft. and the gas (*d*) would also be uniformly distributed through the whole 10 cu.ft. Dalton's law says that the resulting pressure will be the pressure produced by (*c*) plus the pressure produced by (*d*) or $4+16=20$ lbs. pressure of the mixture. This result is just what we would expect, as there is no addition or subtraction of heat energy when the diaphragm is broken and consequently we would not expect any change of pressure.

Dalton's Law. When a mixture of several gases at the same temperature is contained in a vessel, each gas produces the same pressure on the sides as if the other were not there, and the total pressure is the sum of the separate pressures.

Experimental Determination of the Boiling-point. The usual method of finding the boiling-point of a liquid is to boil it in a still (see Fig. 24) fitted with a thermometer and connected to its condenser. As soon after the heat has been applied as the thermometer reading becomes constant, the boiling-point may be directly read.

If only a small quantity of liquid is available, this method is not suitable, and a piece of apparatus, shown in Fig. 22,

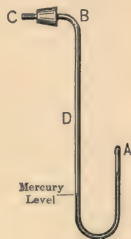


FIG. 22.

is used. It has already been stated that the boiling-point of any liquid depends upon the pressure. The normal boiling-point of water is 100°C. , of course assuming a normal atmospheric pressure of 760 mm. or 14.7 lbs. per square inch. The normal boiling-point of any liquid may be defined as the temperature at which the vapor of the liquid exerts a pressure equal to normal atmospheric pressure.

Directions for Experiment H4-2.

First a closed-arm glass U-tube, as shown in Fig. 22, is nearly filled with mercury. The remainder of the tube is then filled with the liquid to be tested and the end of the tube is closed.

By inverting and shaking the tube a large part of the liquid can be made to pass the mercury and collect in the upper part of the closed arm. The mercury is then jerked out of the open arm until it stands considerably higher in the closed arm than in the open arm.

Suspend the tube in a water bath containing a thermometer. Keeping the water stirred, gradually heat or cool the water until the mercury is exactly level in both arms. The pressure in both arms is then equal. The liquid will then be seen to have partly evaporated, leaving a little liquid above, which will be vapor at atmospheric pressure. The thermometer in the bath under these conditions will read the normal boiling-point.

Liquids having a normal boiling-point above 100°C. will require a bath of sulphuric acid or oil.

If the liquid tends to decompose at its normal boiling-point its boiling-point at lower pressures is frequently obtained. This may be done by applying to the condenser a vacuum pump and manometer in case the still type of apparatus is used, or to the end *C*. in case the U-tube shown in Fig. 22 is used.

Determination of Freezing-point. In Experiment H7-3, the freezing-point is determined from a cooling curve plotted from the readings of a pyrometer or thermometer which is frozen into the solid. This method is used because many substances in passing from the liquid state cannot well be stirred to keep the whole mass at constant temperature and so give a series of readings that are not very easy to interpret. If the energy were given out uniformly throughout the mass, the curve would abruptly stop in its downward direction and proceed in a horizontal line until the liquid had all changed to solid, when the curve would abruptly turn down again.

The curve in Fig. 23 is plotted from data taken in the Pratt Institute Laboratories. Two pounds of lead were heated in a small crucible and after it was thoroughly melted the fire end of a Bristol pyrometer was placed in the molten metal. The heat was turned off and readings of the temperature taken every minute until after the bend *BC* in the cooling curve had been fully passed.

It is noticeable that there is not a sharp turn at either *B* or *C*. This is partly due to the fact that the readings of the pyrometer lag behind the true temperature. The fire-end casing retards the interchange of heat energy between the fire end and the molten metal.

44. Solutions and Mixtures. While it is true that there is no agreement upon the definition of SOLUTION and MIXTURE, the following statements will help the student to become familiar with the terms.

A PHYSICAL MIXTURE is the result of stirring together such substances as chalk and sand, sand and water, oil and water, etc. The substances may be finely divided and uniformly mixed, but the resulting mixture still consists of a large number of two kinds of masses, each mass in turn being made up of a large number of molecules. A solid substance mixed in a liquid can often be separated by a process of filtration by which the solid is strained from the liquid. In cases where the solid is in a very finely divided state, filtration may be accomplished by letting the liquid drain off under pressure through several thicknesses of finely woven cloth or through filter papers.

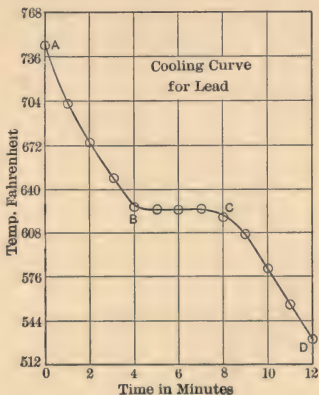


FIG. 23.

SOLUTION is a process that results in a more intimate association of the two substances involved. One of the two substances is usually a liquid and is called the SOLVENT. The second substance, which is added to this, is called the SOLUTE. The molecules of the solute travel as individuals and uniformly distribute themselves by a proc-

ess of diffusion through the solvent. The solution often contains a large number of molecules of the solute, which have also been split up into a positive and a negative ion. Thus the solution which takes place between common salt and water or between alcohol and water produces a very different type liquid from the emulsion or mixture resulting from a rapid shaking together of oil and water.

A solution is said to be saturated when the solvent will take up no more solute.

Some pairs of liquids are soluble in each other in all proportions, alcohol and water for example. In general when dealing with solutions of solids or gases in liquids it is found that there is a definite limit to the amount of solute which a solvent at a given temperature will take up when the solvent is in contact with an excess of the solute.

The solubility of solids is usually expressed as mass of solute dissolved per 100 mass units of solvent. In the case of gaseous solutes solubility is usually expressed as a ratio between the volume of solvent and the volume of solute dissolved.

Temperature has an important effect upon solubility. In general it is true that in all liquid solvents solid solutes are more soluble at high than at low temperatures and all gaseous solutes are less soluble at high temperatures. Boiling a solvent completely drives off all dissolved gases.

These important facts are taken advantage of in the chemical industry in an infinite variety of ways. For example, with salt solutions it is usual to heat the solvent when it is desired to increase the amount of solute dissolved. The liquor is cooled when it is desired to crystallize out some of the dissolved salt. Crystalline solids are often dissolved and recrystallized to purify them. In this event, it is often desirable to crystallize by slowly evaporating the solvent, because the crystals are larger and purer.

Distillation. When it is desired to separate a liquid solvent from a liquid solute or when mixtures of volatile liquors are to be separated a process called distillation is resorted to. Laboratory apparatus for this process is shown in Fig. 24. When a strong solution is heated until it boils, it will usually be found that the gases coming off are mainly composed of the substances having the lower boiling-point. Thus in the distillation of alcohol from water, proof spirits may be obtained from liquors containing only a few per cent of alcohol.

FRACTIONAL DISTILLATION is resorted to when a number of different volatile substances having different boiling-points and different vapor pressures are to be separated. In this case the distillates obtained during each successive rise of a degree or so in temperature are kept separate. The same type of apparatus is used as when it is desired to efficiently separate two liquids at one operation. Various kinds of still heads are used. A still head made of an upright tube filled with glass beads will give 95 per cent alcohol from an 18 per cent liquor. The hot gases rise to the beads and partly condense. The condensed distillate drips backward to the still in a direction opposite to the direction of flow of gases. These gases keep the liquid distillate hot and in a condition to give up volatile gases of high vapor tension and to absorb gas of low vapor tension and with a high boiling-point. At the bottom of the pile of beads the distillate will

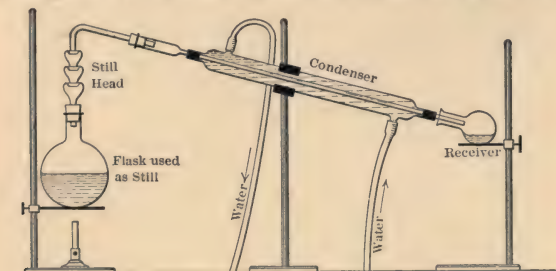


FIG. 24.—Apparatus for Distillation.

be weak in the substance that is being distilled because in its downward path it has taken up excess of the undesirable gas and gives off in its place the substance with the low boiling-point or high vapor pressure. This weak liquor constantly drops back into the still. The still is heated very slowly so that the distillate coming from the condenser will collect at the most efficient rate. In general the efficiency of the process is increased by lengthening the time of contact of the liquid and gas in the still head.

VACUUM DISTILLATION is resorted to when either the solute or distillate tends to change chemically by the heat necessary to drive off the more volatile substance. In the case of mixtures of organic substances this method of separation is very common. The success of the method depends upon the fact that boiling takes place at a much lower temperature at reduced pressures.

Sugar is crystallized out of syrups in vacuum pans, and a great many candies are made in vacuum pans to avoid the chemical changes that result if evaporation and cooking take place under atmospheric pressure at high temperatures. In commercial practice candies are made at temperatures as low as 140°F . A reduction in boiling-point of 35°F is regularly obtained.

Cooling Towers. Fig. 25 shows a cooling tower which may be used in connection with a Refrigerating Plant such as is illustrated in Fig. 61

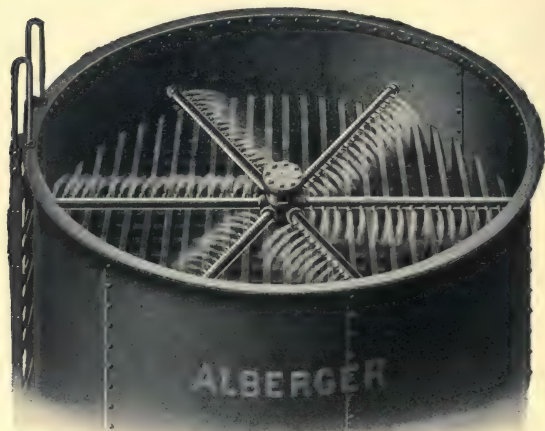


FIG. 25.—View in top of Water-cooling Tower, Showing Distributor.

or with a Steam Power Plant such as is shown in Figs. 46 and 63. The condensers in these plants require a supply of cold water. Where the public water supply is warm or expensive it is desirable to use the same water over again as many times as possible. To accomplish this the water cooling tower is used. Hot water from the condensers is pumped to the top of the tower and is sprayed over the veins and allowed to drop down to a pan at the bottom, where it is again collected. Air is allowed to blow through the tower and as it comes in

contact with the fine streams of water a considerable amount of water evaporates. The latent heat to support this evaporation is taken out of the main body of the water and thereby the water is cooled. The cold water is then returned to the condenser by way of a storage tank.

Digesters are used where cooking needs to be done at high temperatures, to extract oils or to produce various chemical changes. All of these are closed chambers in which cooking is done at a pressure greater than atmospheric. On high mountains these are necessary for domestic cooking on account of the lower boiling-point under the reduced atmospheric pressure.

Fig. 26 shows a laboratory form of digester. Commercial forms of digesters are used in refuse disposal plants, in fertilizer plants, in the cooking of bones and meats, and in the extraction of oils, fats, and greases generally.

Autoclaves are used for both digesting and drying and are steam-heated pressure chambers which can be subjected to pressure or vacuum. Cooking is carried on in digesters by turning on high-pressure steam. The pressure regulates the temperature and for some operations as much as 250 lbs. are necessary. The corresponding temperatures are given by the steam tables.

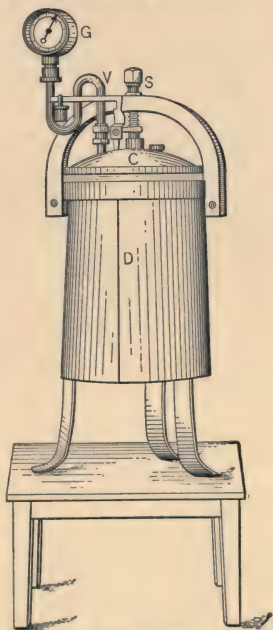


FIG. 26.—Digester.

In Fig. 27 a type of pressure cooker is shown which is now commonly used in mountainous regions for cooking vegetables and foods that are ordinarily boiled. It is claimed that foods cook very much more quickly at a

pressure of about 35 lbs. absolute and require less fuel. The reason for this will be understood if the student will notice in the steam table the temperature at which water boils at 35 lbs. pressure. The slight increase in temperature above 212° F., greatly increases the speed at which the starch grains are broken up and consequently the time required for cooking is reduced.

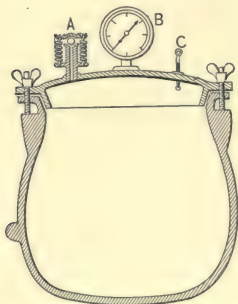


FIG. 27.—Pressure Cooker for Family Use.

45. Analysis of Latent Heat of Vaporization.

Fig. 28 represents a cylinder of indefinite length and of 1 sq.ft. (144 sq.in.) area of base, fitted with a weightless frictionless piston. Suppose there is in it 1 lb. of water at 32° F. This amount of water would occupy $\frac{1}{62.5} = .0160$ cu.ft., and since the area of the base is 1 sq.ft. the water would stand .0160 ft. high in the cylinder. As the upper end of the cylinder is open,

there would be 14.7 lbs. per square inch pressure on the piston or a total of 14.7×144 or 2117 lbs., which would have to be overcome in pushing the piston up.

First Step. Now suppose heat were applied to water. The temperature would rise to 212° F. after 180.5 B.T.U. were applied, and the piston would remain about stationary.

Second Step. As more heat is added, the water is gradually changed to steam and the piston gradually rises to make room for the steam, as 1 lb. of steam at atmospheric pressure requires 26.8 cu.ft. Thus when all water has been converted into steam, the piston has risen 26.8 ft. as in Fig. 29. In doing this it has acted against a pressure of 2117 lbs. and has, therefore, done $2117 \times 26.8 = 56,700$

ft.-lbs. of work. Since 1 B.T.U. does 780 ft.-lbs. of work, to do those 56700 ft.-lbs. must have required $\frac{56700}{780} = 72.8$ B.T.U. Now we know that 970 B.T.U. are given to 1 lb. of water when it is changed to steam at atmospheric pressure. Since only 72.8 B.T.U. of this heat are used up in doing the *external* work or raising the piston, the rest, $970 - 72.8$ or 897 B.T.U., must be used in doing the *internal* work of overcoming the molecular forces.



FIG. 28.

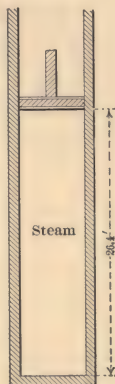


FIG. 29.

The total amount of heat given to the water to change it to steam may then be summarized as follows:

(1) Raising temperature of water from 32° to 212°	180
(2) Overcoming internal resistance.	897
(3) Overcoming external resistance	73

Total heat.	1150
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From the foregoing it will be seen that latent heat of vaporization may be said to be made up of two parts: namely, first, the energy necessary to separate the molecules or to overcome the internal resistance to expansion, and, second, the energy to overcome the external resistance to expansion.

In the steam tables will be found a column showing the external work at various pressures, and in Figs. 32 and 33, pages 128 and 129, will be found curves showing both the internal and the external work. The internal work may be found by subtracting the external work from the latent heat.

46. Relation between the Pressure and Temperature of Steam. The *vapor tension* of water at various temperatures is a quantity constantly entering into the computations of the chemist and the engineer. It is given by various tables and always forms the basis of "steam tables." So common are steam tables that saturated steam is often defined as steam at the temperature and pressure given in the tables. Saturated steam may be expected whenever the *liquid state*, water, and the *gaseous state*, steam, *exist together*. If the steam is saturated any attempt to decrease the volume without a change of temperature will result in condensation of part of the steam. On the other hand, an increase in the volume allotted to the steam will cause it to expand and its temperature to fall below that of the liquid. The pressure will also tend to decrease and the liquid will undergo a lowering of boiling-point. The liquid will then boil violently until a condition of equilibrium is reached.

When a steam boiler explodes, the water in it is at a high pressure before the explosion and consequently above its normal boiling-point. As soon as the boiler lets go, the boiling-point changes and the large amount of energy goes into evaporating much of the water into steam. This accounts for the remarkably large amount of steam that escapes and endangers any who are near.

Since saturated steam is steam in equilibrium with its

liquid phase, water, at the given pressure, the *temperature* of the *saturated steam* is the same as the *boiling-point* of the *liquid* at that *pressure*. Therefore a knowledge of the pressure in any steam boiler also gives us a knowledge of the temperature of both the water and the steam in it by simply referring to our steam tables or to the pressure temperature curves such as are given in Plate 1.

47. Experimental Determination of Relation between the Pressure and Temperature of Steam. In Experiment

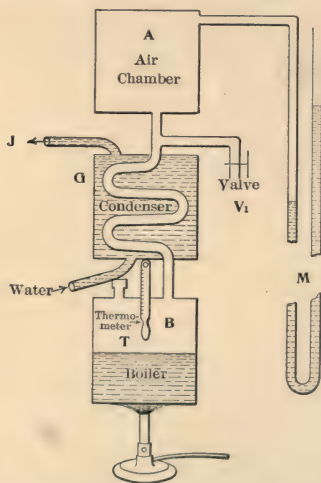


FIG. 30.—Simplified Section of Fig. 31.

31-3 the student determines this relation and plots a curve of his results obtained with the laboratory apparatus. This curve is then compared with one plotted on the same sheet from the data given in the steam tables in the Appendix.

The apparatus used is shown in Figs. 30-31, and is a simple form of that used by Henri Victor Regnault (1810-1878). He made a series of experiments which are

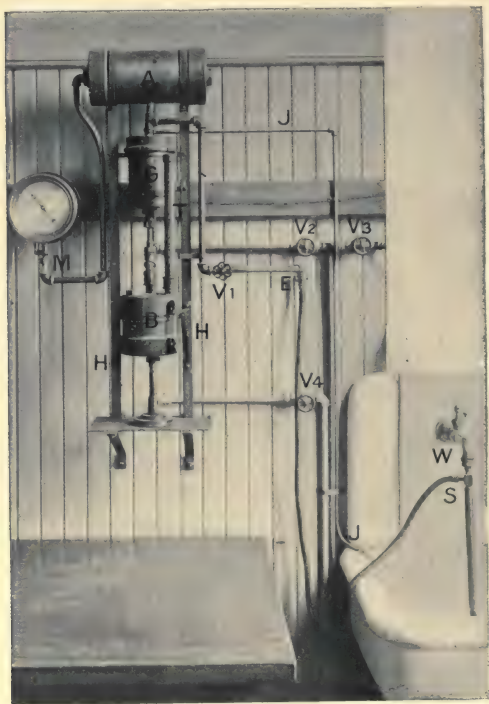


FIG. 31.—Small Boiler for Obtaining the Steam Table Constants.

classical on the properties of water and steam and other liquids and gases. His work has been checked and his

results corrected, but they were remarkably accurate considering the facilities with which he worked.

DIRECTIONS

In abbreviated form the directions for Experiment No. H1-3 follow.

It is desired in this experiment to determine the temperature of steam for pressures ranging from about 3 lbs. per square inch to about 40 lbs. per square inch.

The apparatus is to be arranged as in the diagram. Pressures are controlled by exhausting air from, or forcing air into the large air chamber *A*. Steam is generated in the boiler *B*, which communicates with *A*. A portion of the connecting tube is surrounded by a jacket *G*, through which cold water is passed to condense the steam as formed. Pressure in the closed system is to be measured by a manometer at *M* or by a pressure gauge, and the corresponding temperature of the steam in the boiler is to be read from the thermometer, *T*.

The thermometer should be pushed well down, so that the bulb extends into the body of the boiler. It *must not*, however, *extend into the water*. All connections must be air tight.

In securing readings, first connect tube *E* with aspirator and reduce the pressure in *A* until a difference in level of about 600 mm. is shown by the manometer. Then close the pinch cock at *V*₁, and disconnect from the aspirator. Place the Bunsen burner under the boiler and see that water is passing through the condenser. The burner should at all times be turned down so that the flame will not flare up about the boiler. A small flame will be sufficient at first, as the boiling point will not be high. Continue to boil the water at this temperature until the thermometer ceases to rise—five or ten minutes will probably be required. Then record thermometer reading and the difference in level of manometer columns. Record also height of barometer. Next open the valve at *V*₁, holding the finger over the open ends of the tube meanwhile, and carefully admit air until the difference in level of manometer columns is diminished to about 500 mm. Boil the water at this pressure until the thermometer shows constant temperature and record manometer and thermometer readings as before. Proceed in this way by about equal steps, increasing the pressure 75 to 100 mm. at a time until atmospheric pressure is reached, i.e., pinch cock *E* is left open while the reading is taken.

Then connect the aspirator tube *E* to a compression pump and force air into *A* until the maximum pressure required in the experiment is reached. *Do not force the mercury by the bend in the manometer.*

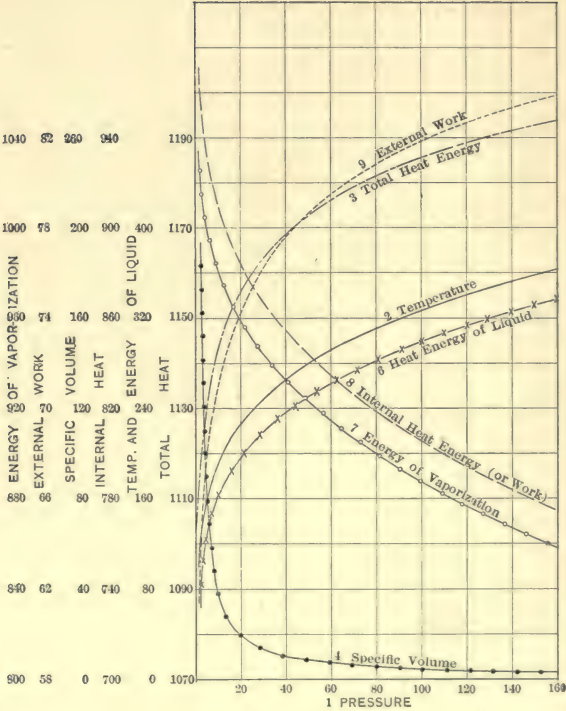


FIG. 32.

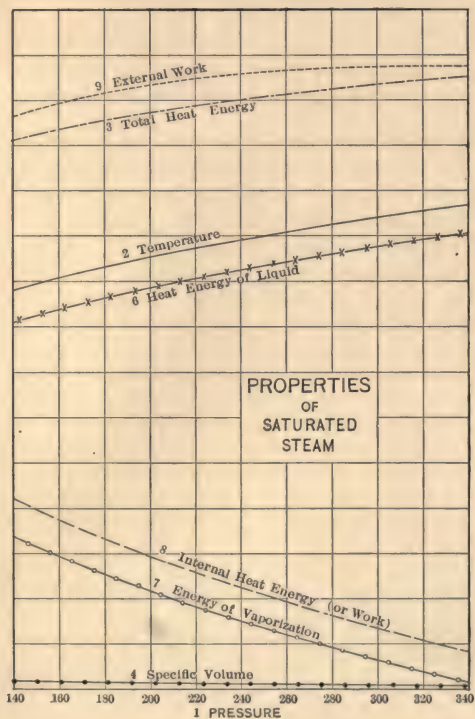


FIG. 33.

Decrease the pressure by successive steps of about 100 mm. as before and take readings until at least ten readings of temperature and pressure have been secured between the lowest and the highest temperatures.

The main precautions to be taken are, to keep the condenser always cold, to allow plenty of time for the thermometer to come to steam temperature, and to keep the flame away from the thermometer tube.

48. Steam Tables. Steam tables have already been referred to as giving the relation between the pressure of saturated steam and its temperature. We may illustrate the use of Table IX by looking up the properties of saturated steam at 235 lbs. gauge-pressure. In Column 1 we find absolute pressure given. Using only the three significant figures, 250 lbs. absolute will be the correct pressure to look up. In Column 2 on the same line, we find the temperature of saturated steam at 250 lbs. absolute to be 401°F . The temperature given on any line is also the boiling-point at the pressure recorded at the beginning of the line. Thus the boiling-point at 250 lbs. absolute is 401°F . Column 3 gives the total heat energy in B.T.U., which must be supplied to 1 lb. of water at 32°F . to raise it to dry saturated steam at a pressure given on the same line in Column 1. At 250 lbs. the total heat energy is 1201 B.T.U. Column 4 gives the volume that 1 lb. of dry saturated steam would occupy at the pressure given in Column 1. At 250 lbs. dry saturated steam has a specific volume of 1.845 cu.ft. The reciprocal of the value in Column 4 gives the value in Column 5. One cubic foot of dry saturated steam at 250 lbs. weighs .542 lb. Column 6 gives the B.T.U. required to heat the liquid to the boiling-point. At 250 lbs., 374.2 B.T.U. are required. Column 7 gives the latent heat; at 250 lbs. the energy to evaporate 1 lb. of water is 826.9 B.T.U. Columns 8 and 9 show this latent heat to be analyzed into 741.5 B.T.U. heat energy to overcome internal molecular forces and 85.4 B.T.U. of external work.

Caution. The student will always remember that the

pressures in the table are absolute, while the customary way of stating boiler pressures is to give the gauge pressure, which is always pressure above atmospheric. Therefore to gauge pressure as given should be added 14.7 lbs. before referring to the table.

Problem 8. How many B.T.U. are required to raise 1 lb. of water from 72° F. to steam at 80 lbs. absolute pressure?

The temperature corresponding to 80 lbs. pressure in the steam table is 312° F.

Heat of liquid above 32° F. = 282.2 B.T.U.

Heat of liquid above 72° F. = 282.2 - 40 = 242.2 B.T.U.

Latent heat = 899.8.

Total heat above 72° F. therefore = 242.2 + 899.8 = 1142 B.T.U., heat required.

Problem 9. How many pounds of water from and at 212° F. would this energy in Problem 1 evaporate?

1 lb. of water from and at 212° F. requires 970 B.T.U., therefore $\frac{1142}{970} = 1.18$ lbs. will be evaporated by 1142 B.T.U.

Problem 10. How many foot-pounds of energy are required to evaporate a ton of water from a temperature of 60° F. to steam at 120 lbs. (gauge) pressure?

The steam table gives the total heat of steam above 32° F. at 120 + 14.7, or 134.7 as 1191 B.T.U. Total heat above 60° F. would be 28 B.T.U. less, or 1163 B.T.U. As there are 778 ft.-lbs. per B.T.U. and 2000 lbs. per ton, the total work in foot pounds per ton = $778 \times 2000 \times 1163$ B.T.U. = 1.81×10^6 ft.-lbs.

Problem 11. How many pounds of water would this energy evaporate from and at 212° F.?

Since it takes 970 B.T.U. to evaporate 1 lb. of water from and at 212° F., the equivalent evaporation will be

$$\frac{2000 \times 1163}{970} = 2400 \text{ lbs. of water.}$$

Problem 12. If coal as fired contains 5 per cent moisture and 13,300 B.T.U. of energy, how much of the energy is required to evaporate this 5 per cent of water and heat it to the tem-

perature of the escaping flue gases, 600° F.? Assume as an average specific heat of steam = .70. Assume the temperature of the coal as fired to be 72° F.

In every pound of coal .05 lb. of water has to be heated from 72° F. to 212° F., evaporated and then the steam heated to 600° F. This requires $.05(140.3 + 970 + 388 \times .70) = 69.1$ B.T.U.

Problem 13. If the dried sample of the coal fired under the above conditions had tested out 14,000 B.T.U. what would have been the available energy from the coal if each pound as fired contained 5 per cent moisture?

Since only 95 per cent was really coal, there was only $14000 \times .95$ or 13300 B.T.U. of energy in the coal. The water wasted 65 B.T.U. and there were therefore only 13,235 B.T.U. of available energy left.

Problem 14. How many pounds of water must circulate through a condenser such as shown in Fig. 24 to distill 5 gals. of absolute alcohol if the circulating water enters the condenser at 40° F. and leaves it at 160° F. and if the alcohol leaves the condenser at a temperature of 60° F.? (Compute according to British system.)

Five gallons of alcohol having a specific gravity of .794 weigh $10 \times .794 \times 5 = 39.7$ lbs. (English gal. of water = 10 lbs.)

If the latent heat of absolute alcohol is 369 B.T.U., the boiling-point 159° F., and the specific heat of the liquid is .59, then the energy lost by the alcohol will equal

$$39.7(369 + .59 \times 99) = 16970 \text{ B.T.U.}$$

Let x equal the weight of circulating water required.
Then the heat gained by the water will equal

$$(160 - 40)x = 120x.$$

Since heat gained = heat lost,

$$120x = 16970,$$

$$x = 141.4 \text{ lbs.}$$

Problem 15. A steam-heated vacuum pan takes out 50 lbs. of water per hour from a sugar solution. If the pan receives steam at 120 lbs. abs. press. and wastes 5 lbs. of steam per hour in keeping it hot, what is the total weight of steam used per hour?

Assume a vacuum in the pan of 28 ins. of mercury or an absolute

pressure of 1 lb., neglect any heat required to heat the solution to the boiling-point, and assume that steam is returned to the boiler as water at 102°F .

Total heat to evaporate 50 lbs. water from and at 101.8°F . $= 1035 \times 50 = 51750 \text{ B.T.U.}$

If x = weight of steam required to yield 51750 B.T.U., the heat given up will also equal the difference between the total heat of steam at 120 lbs. abs. and the heat of the condensed liquid at 102°F . $= 1189 - 70 = 1119x$.

Heat lost = heat gained,

$$1119x = 51750,$$

$$x = 46.2 \text{ lbs.},$$

Total steam = 51.2 lbs.

Problem 16. What temperature can be obtained in a steam cooker or digester using steam at 160 lbs. gauge pressure?

Problem 17. How much energy will be given up to the cooker per pound of steam used if the cooker maintains this temperature?

Problem 18. How much change in the steam consumption in Problem 15 if the pressure of the steam had been 80 lbs. gauge pressure and the pressure in the vacuum pan 2.5 lbs.?

Problem 19. How many pounds of circulating water will be required to condense 10 gals. of ethyl alcohol to a temperature of 100°F ., if the tap water temperature is 60°F . and the overflow from the condenser is at 90°F .?

Problem 20. A boiler evaporates 800 lbs. of water an hour from a temperature of 60°F . at a pressure of 60 lbs. gauge. Find equivalent evaporation from and at 212°F .

49. Superheating Steam. If dry steam is not saturated it will be superheated. Referring to the statements made above it will be seen that if the temperature of steam is reduced and the pressure kept constant, it still remains saturated, but some of it will be condensed. If the *temperature of the gas is increased*, and the pressure kept constant or below that of saturated vapor at the new temperature, the gas is said to be superheated or unsaturated.

Superheated steam is steam at a temperature too high

to agree with that given in the steam table for the pressure at which the steam is confined. Or superheated steam is steam at a temperature above the boiling-point of water for the pressure at which the steam exists.

The total heat of steam is increased about .65 B.T.U. for each degree Fahrenheit of superheating up to 100° F., and averages about .75 B.T.U. for 200° F. of superheating. This variation is due to the fact that the specific heat of steam increases with the temperature.

See Table XI.

REVIEW PROBLEMS, CHAPTER V.

21. How many B.T.U. are required to raise the temperature of 195 lbs. of water from 32° F. to 212° F. and evaporate it?

22. How many pounds of water per lb. of coal can be evaporated from and at 212° F., in a boiler having an efficiency of 75 per cent, using coal containing 13,200 B.T.U.?

23. If dry coal contains 14,200 B.T.U. how much does 5 per cent of moisture reduce the fuel value per pound of coal purchased? Consider only the latent heat of the moisture in this problem.

24. If coal contains 2 per cent moisture, how much does it affect the heat available from the coal if the fuel is stoked at 80° F., and flue gases have a temperature of 560° F.? Express the result in B.T.U. lost per pound.

25. A radiator in a school room was found to use 40 lbs. of dry steam at 5 lbs. gauge pressure in one hour. If the condensed water returned to the boiler through the supply pipe, how much heat was left in the radiator?

26. Coal is burned under a boiler and the products of combustion go up the flue at a temperature of 600° F. The boiler-room temperature is 60° . The coal contains 10 per cent moisture. A sample after drying gives 14,400 B.T.U. per lb. of dry sample. If 20 lbs. of air per pound of wet coal used are required for smokeless combustion, how many B.T.U. go to heat water in the boiler? (Assume no heat lost due to radiation, leaks in boiler setting, etc.)

27. A 25-lb. cake of ice requires how much coal to melt it and warm the resulting water to 78° F.? Coal gives 14,250 B.T.U. per pound.

28. From the B.T.U. per pound latent heat of vaporization of mercury as given in the table, find the calories per gm.

29. Find latent heat of alcohol in B.T.U. per pound.

30. 20 lbs. of lead in a crucible were allowed to cool from a high temperature and a curve plotted. From this it was determined that the rate of change of cooling just before solidification took place was 41° F. per minute and directly after 39° F. per minute. The temperature remained constant for 7.5 min. If cooling was going on at the mean rate obtained by averaging these given above, what must be the latent heat of the lead?

31. What is the efficiency of a boiler which vaporizes 8 lbs. of water at 75° F. to steam at 90 lbs. pressure for every pound of coal burned? The coal has 13,800 B.T.U. per lb.

32. How many foot-pounds of energy are necessary to change 1 lb. of water at 100° F. to steam at 100° F.?

33. How many foot-pounds of energy are necessary to change 1 lb. of water to steam from and at normal atmospheric pressure?

34. How many foot-pounds of energy are necessary to change 1 lb. of ice at 32° F. to steam at atmospheric pressure?

35. If for each pound of coal burned in the boiler furnace 10 lbs. of water at 70° F. are converted into steam at 350° F., what is the ratio of the heat given to the steam to the heat value of 1 lb. of coal, the latter being 14,500 B.T.U.?

36. How many pounds of ice at 32° can be melted by 3 lbs. of steam at 30 lbs. pressure (absolute)?

37. If 4 lbs. of steam at 14.7 lbs. abs. pres. be led into 100 lbs. of water at 42° F., and the resulting temperature is 85.6° F., what is the latent heat of steam at this pressure?

38. A steam boiler evaporates 19 lbs. of water from and at 212° F. per pound of coal used, and the coal costs \$3.50 per ton. Find the cost of producing 1 ton of steam at 80 lbs. pressure from water at 72° F., assuming a constant efficiency.

39. In 1884 the A.S.M.E. defined one B.H.P. as either (1) 30 lbs. of water evaporated from a feed-water temp. of 100° F. to steam at 70 lbs. pressure, or (2) 34.5 lbs. of water evaporated from and at 212° F. From your tables reduce the second value to weight of water evaporated under the first conditions.

40. Plot a curve showing the maximum height to which a vacuum pump can "lift" hot feed water at various temperatures. Plot temperature on the X axis.

41. Suppose a steam drier is so arranged that moisture is driven from coal by the condensation of steam, in coils upon which a steam pressure of 60 lbs. gauge is maintained. The water from the condensed steam drains back to the boiler and remains at the temperature of the steam. The steam heat supplied by the pressure coils evaporates 8 per cent of moisture which is contained in the coal as it is fed at 60° F. 184 lbs. of dried coal is taken from the drier each hour and the temperature of the coal when withdrawn is the same as that of the steam from the boiler. How many pounds of steam must the boiler supply each 10-hr. day?

(Assume no losses by radiation, leakage, re-condensation, etc.)

SUMMARY, CHAPTER V

Certain substances like water are constantly **changing their states during familiar processes**. We describe their condition by such words as solid, liquid, gas, fog, vapor, saturated vapor, superheated gas, dew, relative humidity, vapor tension. The process of changing state we describe as freezing, melting, sublimation, regelation, boiling, condensation, vaporization, etc. **All substances** may have these terms applied to them and **may pass through all of the states mentioned**. We study water because it is the compound most frequently used.

LATENT HEAT OF MELTING is the energy required to change the state of a substance from solid to liquid without changing the temperature.

LATENT HEAT OF VAPORIZATION is the energy required to change the state from liquid to gas without change of temperature.

The amount of the latent heat depends upon the pressure during the change of state.

DALTON'S LAW states that the pressure produced by a mixture of gases in an inclosed space is equal to the sum of the individual pressures that each gas would have if the other gases were taken out of the space in question.

All elements may be made to change state after the manner of water, but some solid compounds cannot be changed to liquids because decomposition results upon

the application of heat. Other compounds may be changed to the liquid state, but they decompose before becoming gases.

PHYSICAL MIXTURES are mass mixtures.

Solutions are mixtures of different kinds of molecules in which the molecules of the two or more kinds travel about as independent units through the mass.

The solute is said to uniformly distribute its molecules through the solvent by a process of diffusion.

DISTILLATION is accomplished by taking advantage of the different boiling-points of the various substances in a mixture or solution to effect a separation.

Latent heat of Vaporization may be analyzed into (1) **External work**, work done against the atmosphere in expanding from the original volume of the water, and (2) **Internal work**, or the work necessary to overcome the molecular forces.

The **PRESSURE-TEMPERATURE** ratio is not constant for steam at a fixed volume; and there is no exact rule for expressing this relation.

STEAM TABLES show this relation as well as the total energy, internal and external work, the specific volume, etc.

SATURATED STEAM at a given pressure has the temperature and specific volume given in the steam tables for steam at that pressure.

SUPERHEATED STEAM is steam at a temperature higher than that called for by the steam tables for steam at the given pressure.

CHAPTER VI

FUNCTIONS OF A STEAM POWER PLANT

THIS chapter does not deal with the design or with the reasons for the special features of the members of a steam plant. It is intended rather to teach the student the fundamental functions of the members necessary for the operation of the plant, and thus to show the reasons for the existence of the members themselves. These reasons for existence are simple and should be thoroughly understood before the student attempts to study the details of construction. The purpose of this book is to prepare the reader for the study of those engineering texts which take up such matters.

50. A Simple Plant. The whole purpose of any kind of a power plant is to get energy out of a fuel or other natural source of energy and to transform it into the mechanical form. In the steam plant the supply of energy is in the coal. This must be liberated, carried to the engine cylinder and then transformed into mechanical energy. Thus there are three distinct processes which must go on: first, the burning of the fuel and the releasing of the energy; second, the transporting of this energy to a place where it can be utilized; and third, the transforming from heat energy into mechanical energy.

In every kind of plant there must be the following essential parts which do these three things:

First. A furnace in which heat energy is freed.

Second. A boiler where the heat energy is delivered to

water and where steam is made. The steam is then carried by piping to the third essential member.

Third. An engine where the energy is taken out of the steam and given to a fly-wheel or other mechanical parts. In small stationary plants, where only a small quantity of energy is transformed, no additional pieces of equipment are commonly used.

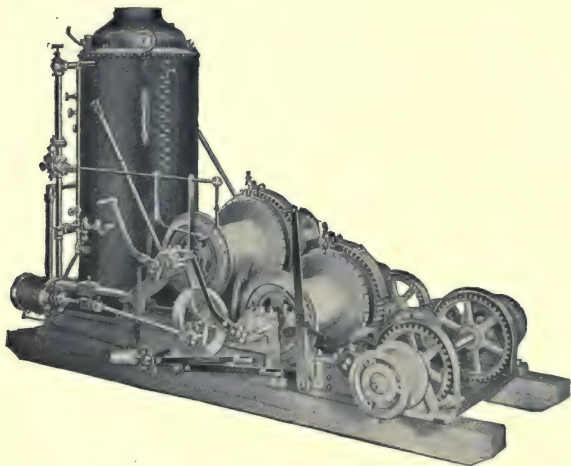


FIG. 34.—Simple Power Plant Operating a Hoist.

Fig. 34 shows a familiar type of portable plant in which the furnace, boiler, and engine are all mounted on a common base. Let us see how this simple plant works.

In the first place water is required in the boiler and a supply must be kept there. We build a fire in the furnace under the boiler and heat the water until it boils and forms saturated steam over the water. If no steam is being used, the continued evaporation or boiling of the water

causes more gas (steam) to be crowded into the space above the water. This produces an increase of pressure. When we want the engine to deliver work (in the mechanical form) we turn a supply of hot steam under pressure into the cylinder of the engine. This cylinder is arranged in a way similar to the engine shown in Figs. 35 and 36. If the engine, when the steam is admitted, stands as shown in the cut, full boiler pressure (abs.) would be applied to the head end of the piston and only the atmospheric pressure would be applied to the crank end to oppose it. The difference between the pressures on the two sides of the piston may be called the **effective pressure** (see section 102). The effective pressure times the area of the side of the piston against which the steam is pressing measures the total force tending to move the piston. As soon as the piston begins to move, the engine starts to do work and then the conditions become more complex.

If the engine runs continuously there must be a continuous supply of coal to feed the fire, of water to feed the boiler, and of steam to feed the engine. The coal is the real source of the mechanical energy and the water, boiler, piping, steam, and steam engine, etc., are all machinery to produce the transformation.

As the piston moves from one end of the cylinder to the other it makes a **stroke**. The pressure during the stroke is never constant. Therefore, in computing the work done per stroke the *average effective pressure* for the entire stroke is always used. This average pressure may be called the **mean effective pressure** (abbreviated M.E.P. See section 102).

The work in ft.-lbs. done for each stroke is M.E.P. in lbs. per sq.in. $\times$ piston area in sq.ins. $\times$ length of stroke in ft. In a typical reciprocating engine, such as is shown in Fig. 35, steam is admitted to both ends of the cylinder alternately. Technically we describe this by saying that an engine is double acting or that both the "forward stroke" and the "return stroke" are working strokes. The

engine in Fig. 36 is making the "forward stroke." The term "forward stroke" is used for the stroke toward the crank.

This type of plant is necessarily very heavily built and roughly adjusted, to stand the hard usage to which hoisting gear is commonly subjected. The manufacturers of this type of plant state that a fair day's work for such an installation is to lift 9700 lbs. 50 ft. once every 75 seconds of a ten-hour working day. The plant which does this quantity of work burns on an average a ton of soft coal each day. The hoisting gear has an efficiency of 80 per

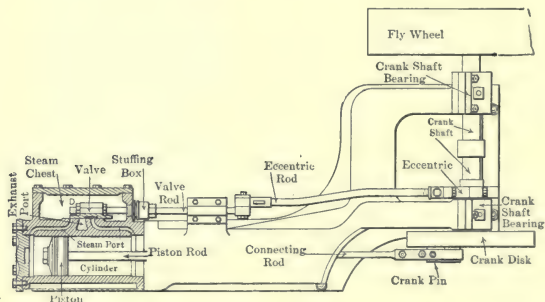


FIG. 35.—Sectional View of Steam Engine Cylinder.

cent. Assuming 13,600 B.T.U. energy per pound of coal, the efficiency of the steam plant is computed as follows:

$$\frac{9700 \text{ lbs.} \times 50 \text{ ft.}}{\frac{75}{60} \text{ min.} \times 33000 \text{ ft.-lbs.} \times 80 \text{ per cent}} = 14.7 \text{ H.P.}$$

$$14.7 \text{ H.P.} \times 10 \text{ hours} = 147 \text{ H.P. hours per day.}$$

Since, according to the manufacturers, one ton of coal is used per day,

$$2000 \div 147 = 13.6 \text{ lbs. of coal per H.P. hour.}$$

The plant efficiency is

$$\frac{\text{B.T.U. in 1 H.P. hr.}}{\text{B.T.U. in 13.6 lbs. coal}} = \frac{2540}{13.6 \times 13600} = .0137 = 1.37 \text{ per cent.}$$

In this, as in every plant, the coal which is supplied is the working capital, for it contains the heat energy from which the plant must be run. The problem is to conserve this capital and make the greatest possible use of the available supply.

There are losses at every step in the series of processes which we have described, and Fig. 37 shows the probable distribution of the losses in this particular plant. Very

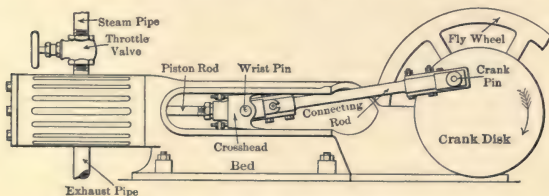


FIG. 36.—Steam Engine Parts.

little attention has been given to investigating and reporting in detail the manner in which all of this energy is lost in the type of plant shown. However, the figures given are a probable approximation.

The energy in 13.6 lbs. of coal is represented in Fig. 37 as passing in a stream, first through the furnace, next after sustaining losses, through the boiler and finally through the engine. The width of the stream represents to scale the amount of the energy at each point along the stream. The losses are indicated by showing a part of the stream as diverted aside.

The surprising fact which this figure and the preceding computation show is that only 1.4 per cent of the energy in the coal was used for useful work. In small plants of

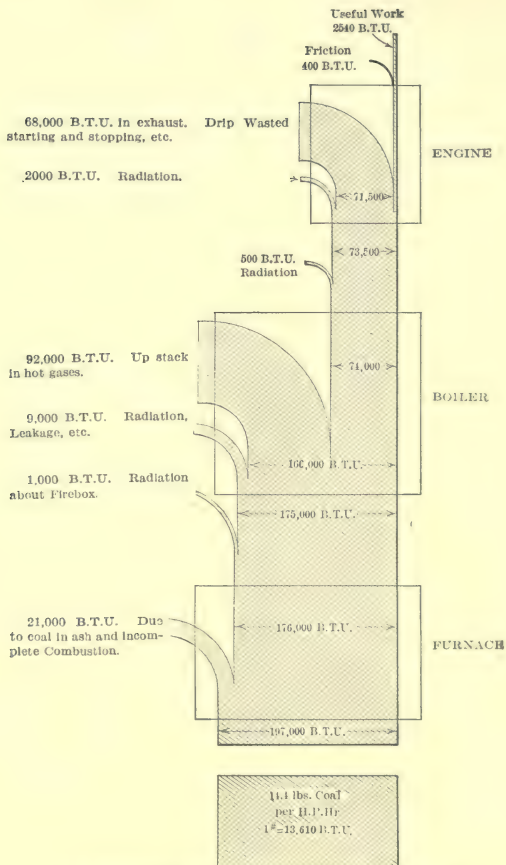


FIG. 37.—Energy Diagram for the Plant in Fig. 34.

this sort, people waste a large part of the coal rather than go to the expense of improving the equipment and use the labor to operate improved equipment economically. In technical language we say that in spite of the apparently low fuel economy, a higher cost economy is thought to result than would be obtained with improved equipment.

Problem 1. What would be the thermal efficiency of the engine in the plant referred to in Fig. 37?

Problem 2. What would be the efficiency of the boiler and furnace in Fig. 37 expressed in the number of pounds of water it could evaporate from and at 212° F. per pound of coal burned?

Problem 3. What per cent of energy delivered to the furnace is transmitted in the steam to the engine in Fig. 37?

Problem 4. If we define a boiler H.P. as 34.5 lbs. of water per hr. evaporated from and at 212° F. (A.S.M.E. rating) what is the H.P. of the boiler in Prob. 2 if the H.P. of the engine is 15?

Problem 5. How much water is required per ten-hour day to run the plant in Fig. 37, if dry saturated steam is delivered at 80 lbs. pressure? Assume a feed-water temperature of 60° F.

Problem 6. A steam power plant uses 8 tons of coal containing 14,000 B.T.U. per pound per ten-hour day. It converts 110,000 lbs. of water from 70° F. to steam at 160 lbs. What is the efficiency of the boiler and furnace in terms of pounds of coal per boiler H.P. hour? (Use A.S.M.E. rating.)

Problem 7. Give the thermal efficiency in per cent in Prob. 6.

Problem 8. If the plant in Prob. 6 averages throughout the day to deliver 600 Brake H.P., what is the over-all plant efficiency in per cent?

Problem 9. Give efficiency in Prob. 8 in pounds of coal per H.P. hour.

Problem 10. If there is 8 per cent waste in coal (92 per cent combustible) give pounds of combustible per H.P. hour.

51. Circulation of Water, etc. In a plant rated at 1000 H.P., or more, attention is given to eliminating losses and to increasing the fuel efficiency of the various members of the steam plant. The plant as a whole is run at a saving of coal by the introduction of members not yet described.

Fig. 38 shows the water circulation in a plant large enough to make it profitable to employ economizers, superheaters,

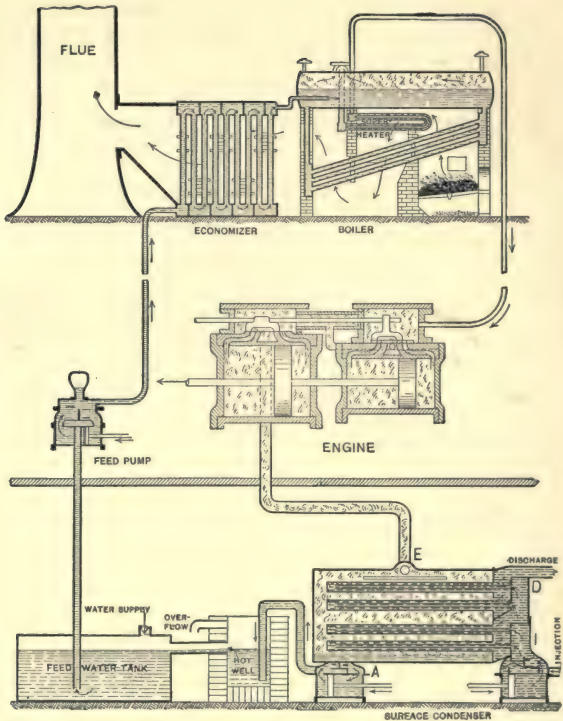


FIG. 38.—Water Circulation in Typical Plant.

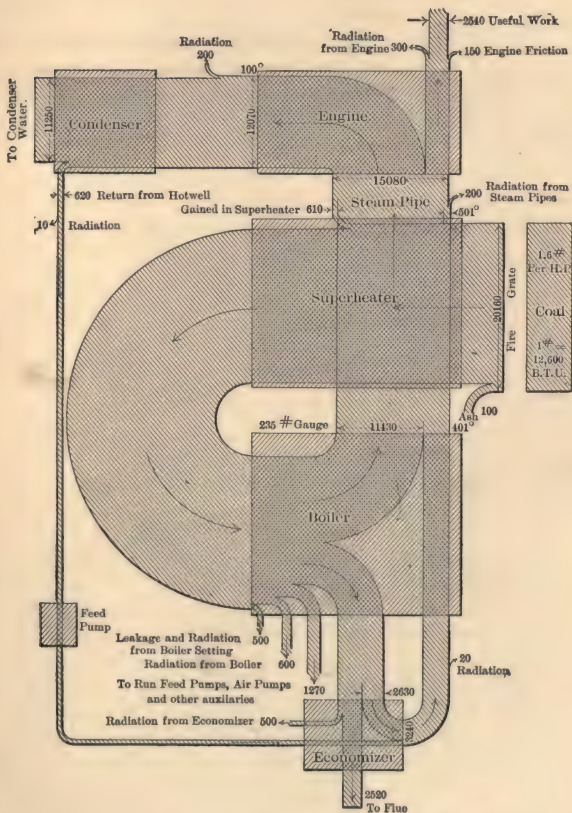


FIG. 39.—Energy Diagram for Plant of Fig. 38

and condensers, with the necessary feed pumps, air pumps, blowers, etc.

It will be noticed that water is forced into the economizer by the feed pump. The water in the economizer is at the boiler pressure and consequently passes into the boiler in a steady stream as fast as it is supplied by the feed pump. The boiler changes the water into steam and the steam passes from the steam dome to the superheater on its way to the engine. The steam is still practically at boiler pressure. The engine takes small quantities of the steam at each stroke and expands the steam in its cylinders down to a low pressure. This steam, which may be exhausted at less than 1 lb. pressure, contains a large amount of moisture, and the mixture of steam and water is passed into the condenser. The wet vacuum pump, shown at the lower left-hand side of the condenser, maintains the vacuum in the condenser and also pumps the water out of it. This water may now be used as supply water for the feed pump and circulated through the economizer, boiler, engine, and condenser an indefinite number of times. Except for leakage no loss of water takes place in such a system.

It will be noticed that there is a separate water circulating system used to keep the condenser cool. By carefully examining the surface condenser, the student will see that the "injection water" is pumped by the pump at the lower right-hand side through an independent set of piping. The water is forced in at *I* and out at *D* without coming in contact with the steam. The water rises from *I* to *D* but the steam falls from *E* to *A*. Thus it will be seen that these currents run in opposite directions. We say that the apparatus acts upon the counter-current principle.

The flow of gases should also be observed from Fig. 38. It should be remembered that the air after passing through the fire-bed and supporting combustion becomes very hot, and is changed in chemical composition. The resulting hot

gaseous products pass over the head ends of the water tubes. After delivering a portion of their heat energy, the gases reach the superheater. As indicated by the arrows, the gases are deflected by the baffle plate after heating the superheater tubes, pass down over the boiler tubes again and are made to pass up over the water tubes a third time before entering the economizer. From the economizer the gases pass up the stack.

52. Energy Circulation. To study the way in which the energy in the fuel is transformed to mechanical energy by the plant, let us examine Fig. 39.

An attempt is here made to find what becomes of the energy from 1.6 lbs. of coal containing a total of 20,160 B.T.U., as a test showed that this was the average weight required per H.P. hour. The energy is represented as a stream which is considered to be passing from the coal through the firebox, superheater, boiler, etc. As has been stated, the superheater in this case was inside the boiler setting, but for purposes of analysis it was thought best in this diagram to consider the boiler and superheater as being separate members.

As in Fig. 37 the width of this stream represents to scale the relative amounts of energy flowing through each part of the plant and losses are shown by indicating that a part of the stream has been diverted to one side.

The energy is released in the furnace, but the process is not complete and a certain amount of coal is dropped into the ashpit and wasted. 100 B.T.U. are shown to be lost thus. The steam in the superheater is shown to gain 610 B.T.U. by being superheated 100° F. above the boiler temperature. The superheater is not shown as having any losses, as all of the radiated heat is available for the boiler, since the superheater is in the boiler setting. The boiler, however, and the boiler setting (which is really part of the furnace) are charged with a total loss of 1100 B.T.U., due to radiation and leakage. Some of the steam generated

in the boiler must be used to run auxiliaries such as pumps, blowers, etc., and therefore must be charged up to the plant as a loss.

After the products of combustion pass out of the boiler setting into the economizer, they still contain 5650 B.T.U. of heat energy. 500 B.T.U. are shown as lost in radiation and 2520 B.T.U. are shown as going up the flue and serving no useful purpose except as they contribute to the draft. The economizer saves 2630 B.T.U. which would otherwise go up the flue. This energy stream is carried back to the boiler as the feed pump forces the water through the economizer to the boiler. As the water drawn from the condenser is somewhat warmer than tap water, 610 B.T.U. are shown to be saved by using the water from the condenser over again. This saving is from the energy thrown into the condenser by the engine. The total saving by the economizer is therefore $610 + 2630 = 3240$ B.T.U., which is returned to the boiler.

In the boiler the water is changed to steam. Some of the steam is used in the auxiliaries and for service purposes about the boiler house. The greater part of the steam is delivered to the superheater and passes on to the engine. In the superheater the 610 B.T.U. already referred to are taken up to raise the temperature above that of saturated steam at 235 lbs. pressure.

In this analysis it was assumed that the steam was dry when it came from the boiler. If the quality of the steam was poor (that is, if the steam contains some water) the superheater supplied some of the energy shown in the diagram as supplied by the boiler. This very likely was the case, but when the quality is very good (or as we sometimes say, when the quality is nearly 1) it is not easy to detect the small amount of water present. If, however, the quality had been 995, it would have required .5 per cent of the latent heat at 235 lbs. to evaporate this moisture. To each pound of steam used the superheater would have then added $(.005 \times 827) = 4.1$ B.T.U. additional.

The engine is seen to have an energy stream of 15,080 B.T.U. flowing in. Of this, it loses in radiation 300 B.T.U. and throws into the condenser 12,070 B.T.U. 2540 B.T.U. (or 1 H.P. hour) have appeared as useful work or energy in the mechanical form at the fly-wheel. There was an additional amount, 150 B.T.U., of mechanical energy transformed which was used up in overcoming the friction of the moving parts of the steam engine.

This energy (2540 B.T.U.) is delivered at the fly-wheel and could be measured with a Prony brake or other suitable means. The indicated horse-power (I.H.P.), however, is not available from the data given in the figure. The I.H.P. is the actual rate of delivering mechanical energy to the piston and is obtained by finding the M.E.P. by means of a Watts Indicator (see Chapter XI). Then

$$\text{Power} = \frac{\text{Force in lbs.} \times \text{distance in ft. per Min.}}{33000 \text{ ft.-lbs.}},$$

For the forward stroke

$$\text{I.H.P.} = \frac{\text{M.E.P.} \times \text{Area piston in sq.in.} \times \text{R.P.M.} \times \text{Length stroke in ft.}}{33000 \text{ ft.-lbs.}},$$

or more briefly:

$$\text{Forward Stroke I.H.P.} = \frac{\overset{\text{force}}{(\text{M.E.P.} \times \text{A})} \times \overset{\text{distance}}{(\text{R.P.M.} \times \text{L})}}{33000 \text{ ft.-lbs.}}.$$

If the engine is double acting, care must be taken to obtain the M.E.P. for both ends and to make correction for the cross-section area of the piston rod on the crank end of the piston. It is best to compute I.H.P. developed by each end and add the power from each end to get the total I.H.P. Thus

For the return stroke

$$\text{I.H.P.} = \frac{(\text{M.E.P. crank end} \times \text{Area crank end}) \times (\text{R.P.M.} \times \text{L})}{33,000 \text{ ft.-lbs.}}$$

and

$$\text{Total I.H.P.} = \text{Forward I.H.P.} + \text{Return I.H.P.}$$

The difference between the I.H.P. and the B.H.P. is the power lost in the engine. This loss is due to the friction of the piston, and the friction of the various bearings. Part of the energy used to overcome friction is at once converted back into heat within the cylinder and is carried off in the exhaust or by radiation from the surface. Because this information is not shown in the energy diagram (Fig. 39) the I.H.P. cannot be computed in this case.

The mixture of water and steam is exhausted from the engine into the condenser. In the figure, a surface type of condenser is shown and in this type the exhaust passes down over the outer surface of successive layers of piping containing cold circulating water. The steam and the circulating water do not mix at all, but the steam gives up its latent heat to the pipes kept cold by the water. This condenser is like that shown in Figs. 44 and 45.

The condensed water in the case under discussion is pumped out by an air pump (sometimes called wet vacuum pump) and is then available to be fed again to the boiler.

53. The Energy Stream is seen to flow on steadily through each member of the steam plant. It is the aim of both the designing engineer and the operating engineer to see that the least possible amount of energy is lost in each member. There has been a constant study of all the details of the construction and operation of steam power plants to this end. Through the invention of new processes of manufacture, new materials, new improvements in design, and the increase in the size of the plants and of the engine

units, the possibilities of *great* improvement in the existing types of steam plants have been exhausted. The best that can be done is to study each member, determine the cost of coal, and the other cost relations for the town where the plant is situated and select the type of equipment and plan of operation which gives the lowest operating cost.

Problem 11. What per cent of energy entering the engine of Fig. 39 appears as useful work?

Problem 12. What per cent of the energy in the coal is turned into useful mechanical energy by the plant under discussion in Fig. 39?

Problem 13. What per cent of energy available for the superheater, boiler, and furnace was not wasted in Fig. 39?

Problem 14. What per cent of the energy in the coal was saved by the superheater? (Fig. 39.)

Problem 15. What was the weight of water used by the engine per Brake H.P. hour, if the water from economizer was at 350° F.? (*The water rate* is usually the weight of water per I.H.P. hour.)

Problem 16. Assuming the steam delivered by the boiler to be dry, how many degrees was the steam superheated in Fig. 39?

Problem 17. From the data in Fig. 37 compute what per cent of the energy in the coal is available for steam heating, if the exhaust steam is piped into a building. What per cent of the energy is available in Fig. 39?

Problem 18. If 14 lbs. of water at 80° F. per Brake H.P. hour was circulated through the economizer in Fig. 39, what was the boiler feed-water temperature?

Problem 19. If the auxiliaries of the steam plant in Fig. 39 use on the average 80 lbs. of saturated steam per Brake H.P. hour developed by auxiliary units, and if the total weight of water evaporated by the boiler per hour was 15,000 lbs., what Brake H.P. was being developed by the various auxiliaries of this plant? (Note that the water leaves the boiler as steam by only two paths.)

Problem 20. If the injection water in the condenser of the plant shown in Fig. 39 was at a temperature of 56° F. and the discharge at 80° F., what weight of water must be circulated if 15,000 lbs. of steam per hour was evaporated, the auxiliaries were run as a condensing engine, and the total weight was thrown in at *E*? (Assume diagram to be worked out for 15 lbs. of steam.)

Problem 21. In Problem 20, what was the pressure and quality of the steam entering the condenser?

It is not the object of this chapter to teach the details of construction of each common device or member of the steam plant. The foundation of theory which will help the student in the use of other books is all that space will allow. A few members and types are discussed by way of illustration.

54. The Steam Boiler. A typical boiler is shown in Fig. 40, and the student is requested to notice that the

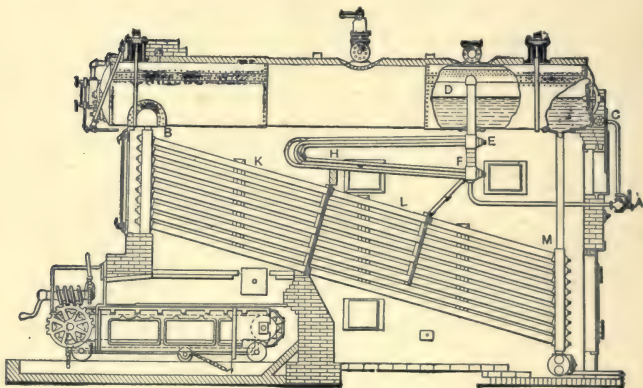


FIG. 40.—Babcock and Wilcox Boiler with Mechanical Stoker.

water drops down the back water leg *M* and rises in the inclined water tubes to the front header *B*. As the water circulates it takes up heat energy from the furnace and thus some of the water is evaporated before entering the front header *B*. The presence of steam in the water makes the mixture of water and steam weigh much less per unit volume in the front end of the tubes than in the back water leg, and this difference in weight causes the convection currents or the circulation of the water.

In Fig. 41 is shown a Sterling boiler. This is a quick-steaming type, because it holds less water per rated H.P.

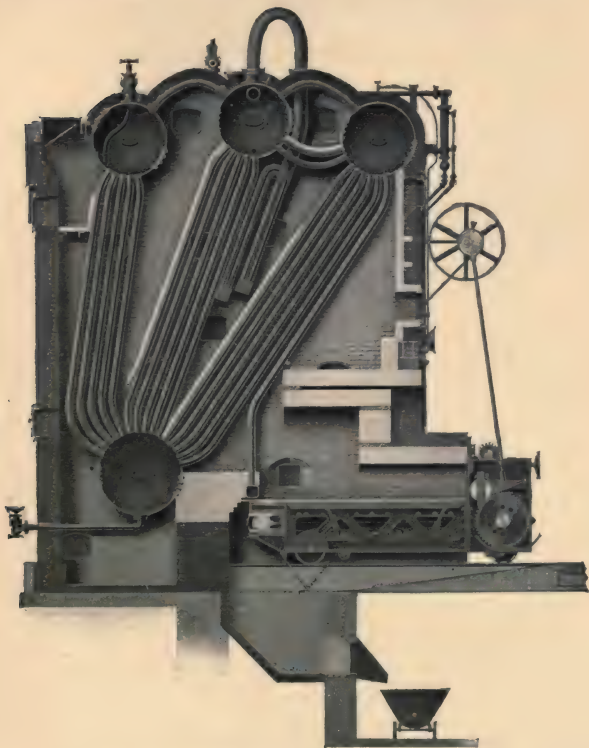


FIG. 41.—Sterling Boiler with Mechanical Stoker.

There are three so-called steam drums at the top and a mud drum at the bottom, but the amount of water carried

by the four is much smaller than in the boiler shown in Fig. 40. Baffles are placed behind the first and second banks in such a way as to compel the gaseous products of combustion to pass first over the first bank of tubes, second, through the superheater and down between the tubes of the second bank; third, up along the third bank.

As has already been stated, it is usual to define a **BOILER HORSE-POWER** as the capacity to evaporate per hr. 34.5 lbs. of water at 212° F. to steam at 212°. However, steam is seldom made under these conditions, and so it is necessary to compute the equivalent evaporation from and at 212° F. for each set of conditions met. If steam at constant pressure is being generated from feed water at constant temperature, the heat per pound of water added by the boiler will be constant. The ratio between this quantity and the heat necessary to evaporate from and at 212° F. is also a constant, and is called the **FACTOR OF EVAPORATION**. This factor is useful in computing the results of boiler tests.

Factor of Evaporation =

$$\frac{\text{Total heat in steam} - \text{total heat in feed water}}{970},$$

where, Total heat in steam = latent heat at boiler pressure $\times$ quality + sensible heat
(see Steam Tables);

Total heat in feed water = sensible heat of the feed water as it enters boiler;

970 = latent heat at 212° F.

Problem 22. In a given boiler test, water was fed at 170° and 99 per cent quality steam at 190 lbs. gauge was delivered by the boiler. Find the Factor of Evaporation.

Total heat in feed water above 32°.....	138 B.T.U.
Total heat in steam at 205 lbs. gauge.....	1198 B.T.U.
Latent heat of steam at 205 lbs. pressure or at 383° F.	842 B.T.U.

If 1 per cent of the original water is not yet evaporated but is floating as a mist in the steam at 220 lbs. absolute pressure, the total energy will be less than given in the steam table by 1 per cent of the latent heat, or

$$8.4 \text{ B.T.U.}$$

Heat contributed by the boiler

$$(1198 - 8.4 - 138) = 1052 \text{ B.T.U.}$$

$$\text{Factor of Evaporation} = \frac{1052}{970} = 1.085.$$

55. The Efficiency of a Steam Boiler is the technical name commonly used for the combined efficiency of the *boiler, furnace, and grate*.

The practice in the numerical computation varies. Properly the combined efficiency of a grate, furnace, and boiler should be the quotient of the energy in the steam added and delivered by the boiler, divided by the total energy in the fuel stoked. In this case the energy in the steam would be computed by multiplying the weight of steam delivered by the difference between the total heat in the steam and the heat in the feed water.

$$\text{Boiler Efficiency} = \frac{\text{added B.T.U. delivered in steam}}{\text{B.T.U. in coal}}.$$

For purposes of comparison of boiler performance it is usual to compute the heat energy transmitted to the water, and divide this quantity by the weight of combustible. (Heat energy transmitted to the water is equal to the water evaporated per pound $\times$ heat gained per pound in the boiler. The weight of combustible is the total weight of fuel minus the weight of ash and coal taken from ashpit.) This quantity is sometimes called the efficiency of the boiler or **FUEL EFFICIENCY**. Often the efficiency is stated in terms of the pounds of steam delivered per pound of com-

bustible burned, but it may more properly be called the combined efficiency of the furnace and boiler. Instead of using the weight of the combustible in the coal to compute the FUEL EFFICIENCY, frequently the weight of steam per pound of fuel as stoked is given. The weight of steam is usually the equivalent weight which could be evaporated from and at 212° F., but the computation and results must be inspected each time to be sure of them. The steam tables in use previous to 1911 have values differing from those given in Marks & Davis' steam tables, and in the 1911 edition of Peabody's steam tables by as much as .5 per cent in some cases.

The **Water Rate** is usually computed as the pounds of steam and water per I.H.P. hour passing through the cylinder. It is sometimes computed on a B.H.P. hour basis or a K.W. hour basis.

All of these irregularities in the practice of engineers reporting tests require that the data from tests be inspected with care to determine just what the results mean. The student should always go back of the "label" or term used and see that the author means the same thing that the student has been taught is good usage. The student must be prepared to convert results expressed in any of the ways indicated to equivalent results under any other set of conditions. Only in this way can valuable results for comparison be obtained.

In Appendix E will be found the recommendations as to the use of these terms given in the Preliminary Report of the Power Test Committee Code of 1912.

Problem 23. If the feed-water temperature in Fig. 39 had been 240° F., what would have been the equivalent evaporation from and at 212° F.? (Assume 15 lbs. of water evaporated.)

Problem 24. In Fig. 37, if the feed-water temperature was 70° F. and the steam pressure was 80 lbs. gauge, how much water per pound of coal was evaporated by the boiler?

Problem 25. In Fig. 39 what was the equivalent evaporation

of water per pound of coal from and at 212° F. if the water left the economizer at 365° F.?

Problem 26. What was the Factor of Evaporation in Problem 23? (See *d*, page 323.)

Problem 27. What was the Factor of Evaporation in Problem 24?

Problem 28. How much water could the boiler in Fig. 37 evaporate if its efficiency were not changed, if the boiler feed-water temperature was 80° F. and the steam pressure was 75 lbs. gauge?

Problem 29. If sample 10 in Table IV were burned under a boiler whose combined efficiency with the furnace was 75 per cent, if the feed-water temperature was 85° F. and if the boiler pressure was 200 lbs. gauge, what weight of water would be evaporated?

Problem 30. If the quality of the steam was 985 as it was drawn from the boiler in Problem 28, what weight of water would be evaporated?

Problem 31. If in Fig. 39, the boiler feed water entered at 200° F. and at the rate of 15,000 lbs. of water per hour, how many boiler H.P. (A.S.M.E. rating) were the boilers and superheaters developing?

Problem 32. If the coal used in Fig. 39 contained 14 per cent of waste, and the boiler feed temperature was 180° F., what was the equivalent evaporation per pound of combustible from and at 212° F.?

56. Feed-water Heaters and Economizers. A boiler shell should not be subjected to sudden changes of temperature, either locally or as a whole. The resulting contraction produces serious strains, cracks, and sometimes explosions. Therefore, some means of supplying a boiler with water at approximately boiler temperature is a very important consideration. For large plants the economizer can usually be introduced with a sufficient saving in fuel to make the large investment profitable. An ECONOMIZER heats the feed water. The waste gases which have passed over the boiler tubes still contain considerable heat energy. They are made to pass over the economizer tubing on the way to the chimney, thus giving up to the feed water a part

of this energy which would normally be wasted. The introduction of an economizer makes it possible for the boiler to evaporate a larger weight of water per hour. Resistance is added to the flow of the flue gases, but usually plants have more than the necessary draft. It is also true that the fire may be burned at a considerably faster rate with economical results. (See Fig. 42.) When the engines of a plant

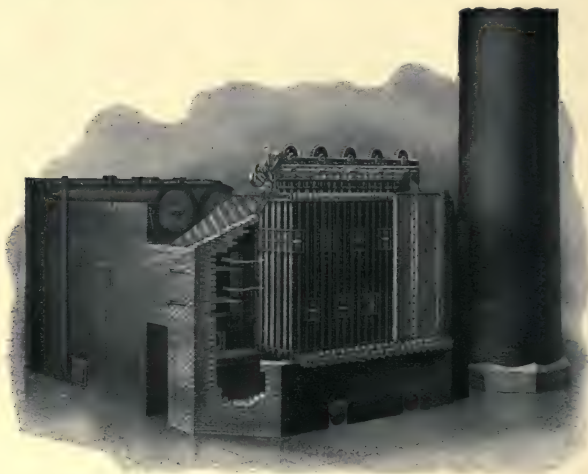


FIG. 42.—Green Fuel Economizer.

are run non-condensing it is generally more economical to use a feed-water heater. A **FEED-WATER HEATER** uses the exhaust steam of the engines as its source of heat energy. In Fig. 43 is shown a type in which the exhaust steam comes in direct contact with the water.

In either case, whether the feed is preheated by a

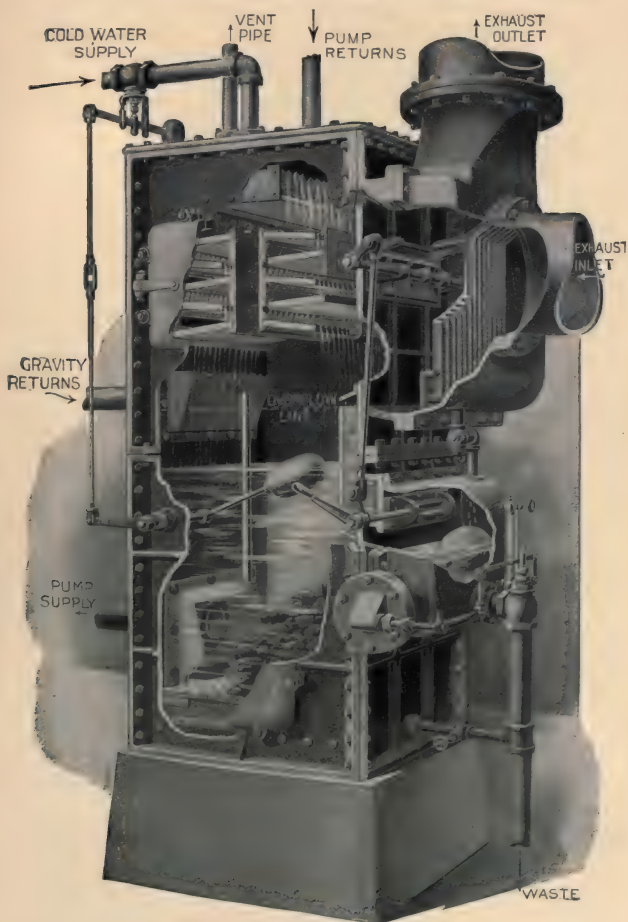


FIG. 43.—Cochran Feed-water Heater.

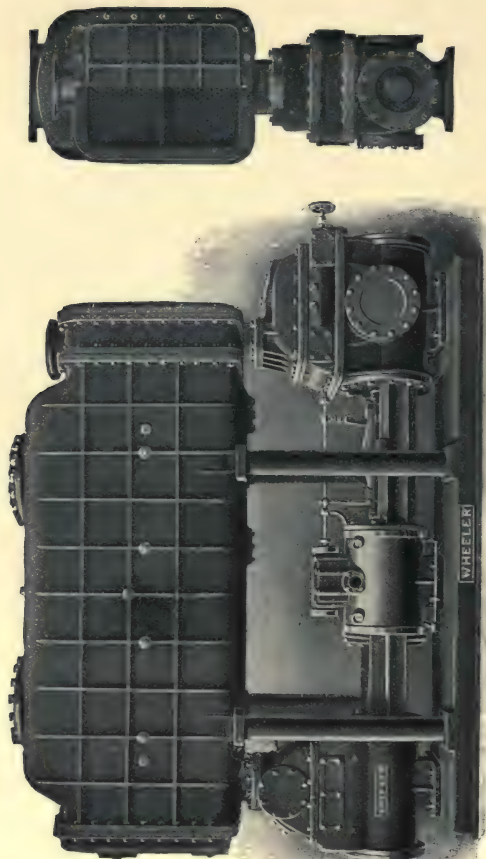


FIG. 44.—Wheeler-Admiralty Surface Condenser with Air and Circulating Pumps.

feed-water heater or an economizer, waste energy in the form of flue gases or exhaust steam is utilized, and this accounts for the fact that such units increase the efficiency of steam plants.

57. Condensers. There are two types of condensers,

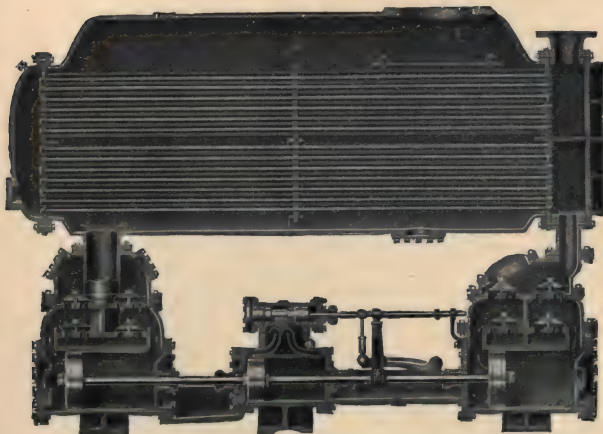


FIG. 45.—Sectional View of Surface Condenser with Air and Circulating Pumps.

the Surface Condenser and the Jet (or Barometric) Condenser.

Surface Condenser. This condenser is like that shown in Fig. 38 and has the counter-current circulation. (See the discussion on Page 148.) This counter-current principle is used in a great variety of industrial processes. Wherever a heat transfer through a condenser of any type occurs, where a solute is interchanged through a porous membrane by osmotic pressure (as in sugar purification) or where

fractional distillation is being performed, it is used with especial frequency.

The steam is hot at the top and after being condensed to water trickles over the pipes to the bottom and gradually cools to approximately the temperature of the pipes at the bottom. The cold water enters at the bottom, where it first comes in contact with the coldest condensed water and tends to absorb some of its sensible heat. Warmed by this small quantity of energy it rises to pipes in contact with the steam, where it receives the relatively large quantity of latent heat which the steam must give up. The circulating water is discharged at the top, from which point it may be pumped to a cooling tower and, after being sprayed over lattice work and cooled by the evaporation of part of it in the air, the remainder may be injected again into the condenser. In coast towns and on shipboard the water which is injected into the condenser may be drawn from the ocean and the hot discharge water which leaves the top of the condenser allowed to flow back. If the plant has a plentiful supply of artesian well water, the cooling tower is unnecessary.

The primary advantage of using a condenser in a steam-power plant lies in the fact that the condenser reduces the back pressure upon the engine. When a condenser is used the amount of the back pressure in pounds per square inch is numerically determined by subtracting the vacuum expressed in inches of mercury from the barometer reading and dividing by 2.04.

Jet Condenser; Fig. 46, shows the water circulation in a plant served by a jet or barometric condenser. A dry-vacuum pump is piped to the top of the mixing chamber at *F*. Water is pumped up to a level from which the vacuum in the chamber can draw or siphon it the remainder of the way into the mixing chamber.

Fig. 47 shows both a cut-away section and a sectional drawing of the barometric condenser of Fig. 46. The

circulating water enters at *B* and impinges upon the cone *C*, which causes the column of water to be broken into a spray. Exhaust steam enters at *A* and coming in contact with the spray is quickly condensed. The bottom of the chamber *H* is piped to a hot well, the water level in which must be at least 35 ft. lower than *H* if the vacuum is to be maintained.

The pipe *E* leads a portion of the cooling water to the

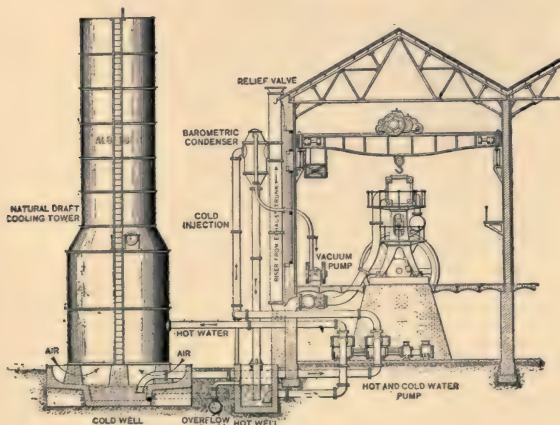


FIG. 46.—Section of Plant Showing Water Circulation.

large space in the head of the condenser. This cools the air well below the temperature in the region *G*, *H*, and greatly reduces the weight of water vapor drawn out through *F*.

An incidental advantage resulting from the use of a surface condenser in a steam-power plant is that once the water has been evaporated in going through the first cycle of operations it is freed from the salts which incrust the inner

surface of boilers and boiler tubes (and form boiler scale) when hard water is fed to the boiler.

58. Steam-engine Functions.

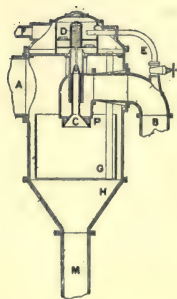


FIG. 47.—Sectional View of Alberger Barometric Condenser.

All heat engines are intended to produce mechanical motion when supplied with a compressed gas. As a first principle of theory we may say that it is the pressure of the gas upon the piston of a reciprocating steam engine which makes it move. Of course, the reader will remember that it is really the difference in pressure between the two sides, for normally there will be a back pressure on the side opposite to the working fluid due to the atmospheric pressure, or the condenser pressure. In a steam turbine we must have the gas under pressure. By passing the gas through a nozzle it is given a high velocity. A good mental picture of one type of turbine will be obtained if the student thinks of this rapidly moving gas as a "howling hurricane" blowing through a greatly improved type of enclosed windmill. Thus, the turbine, which we have likened to a windmill, delivers mechanical

energy with approximately the same efficiency as the ordinary type of reciprocating steam engine. Because of the absence of reciprocating parts the turbine is an extremely convenient type of engine. For driving electrical generators

it is especially desirable, because of its naturally high speed and pure rotary motion.

To fully discuss the relation that the pressure of steam bears to its energy available for useful work in an engine requires a more extended study of the relation between the temperature, pressure, volume, and quantity of heat energy. Chapter X is largely devoted to a discussion of this topic, but the student should consult a text in Thermodynamics for more complete information.

The most essential point about engine theory for the practical man to understand is that the useful work done by any steam engine must be taken from the difference between the energy in the steam admitted and the energy in the exhaust steam. Over two-thirds of the total energy in steam above 32° is in its latent heat. It is evident, therefore, from a purely theoretical standpoint, the more water in the exhaust the more energy has been left in the engine.

The following problem is worked out to illustrate this important point. Given the following data:

Pressure in steam chest of engine.....	235 lbs. gauge
Steam exhausted into condenser exerting a total back pressure of.....	1 lb. gauge
Steam admitted and exhausted in a dry and saturated condition.	
Total energy per lb. of steam admitted (see steam table).....	1201 B.T.U.
Total energy in 1 lb. of steam at 1 lb. (ex- haust) pressure.....	1104 B.T.U.
Total heat energy left in the cylinder under the above conditions (1201-1104).....	97 B.T.U.
The water rate for this engine per brake H.P. hour is $2540 \div 97$	26.2 lbs.

This is over twice as much steam as a modern engine would use under such conditions. If the engine in this

illustration had used 10 lbs. of water per H.P. hour and there were no losses by radiation, leakage, etc., in the engine, each pound of steam would have left 254 B.T.U. in the cylinder. (254-97) or 157 B.T.U. of this energy must have been latent heat of the water. Since the heat energy of vaporization for 1 lb. pressure (gauge) is 1034 B.T.U., there must have been $157 \div 1034$ or 16.1 per cent of moisture in the exhaust steam. From these two problems it follows that the more efficient an engine is, the greater will be the percentage of moisture in the exhaust.

The efficiencies which would result from exhausting dry saturated steam will be computed in the following instructive but impractical problems:

Problem 33. A steam-power plant has a boiler pressure of 80 lbs. abs. and takes feed water from its condenser, which has a pressure of 1 lb. abs. If the engine received and exhausted dry saturated steam, what is the maximum per cent of the energy received by the water in the boiler, which could be transformed by the engine into useful work?

From steam table we will see that under 1 lb. pressure the exhaust steam and consequently the condensed feed water returned to the boiler will be at 102° F. Steam under 80 lbs. in the boiler will be at 312° F. and have a total heat above 32° F. of 1182 B.T.U. We must subtract from this the heat energy already in the water at 102° F. or 70 B.T.U. total heat above 32° F. per lb. of feed water.

$\therefore 1182 \text{ B.T.U.} - 70 \text{ B.T.U.} = 1112 \text{ B.T.U.}$, the heat energy received from fuel.

The steam exhausted at 1 lb. pressure has a total heat above 32° F. of 1105 B.T.U.

Then $1182 \text{ B.T.U.} - 1105 \text{ B.T.U.} = 77 \text{ B.T.U.}$ left in engine cylinder, or *output*. $\frac{77}{1112} = .0691$ or 6.91 per cent converted.

Problem 34. What would be the maximum per cent of transformation possible if the plant is taking feed water at 102° F. and exhausting into atmosphere, under conditions expressed in Prob. 33?

Problem 35. In above example, what would be the maximum

per cent of transformation if feed water were taken at 200° F. and engine exhausted into the atmosphere?

Problem 36. If boiler pressure in Problem 33 had been 200 lbs., what maximum per cent of transformation would have resulted?

Problem 37. If boiler pressure in Problem 34 had been 200 lbs., what maximum per cent of transformation would have resulted?

59. The Rankine Cycle is the heading under which is discussed in most books a set of hypothetical conditions which are assumed to exist in a steam engine. In speaking of Fig. 38 it was made clear that the water could be used over and over again. Each time a given pound of water has completed a round trip through the apparatus and attained the original condition we say it has completed **one cycle**. The discussions of Carnot's cycle, and Rankine's cycle both assume ideal conditions, but Rankine's cycle is more directly applicable to practical engines because it deals with water and steam as the working medium rather than a perfect gas.

In the Rankine cycle it is assumed that the cylinder used has non-conducting walls, no clearance, no leaks, no friction, and is in every way perfect. While these conditions cannot exist in practice, the Rankine cycle fixes the *limit of perfection* toward which we may work in engine design. In discussing the indicator cards of actual engines, engineers frequently give the efficiency of the engine as the ratio between the I.H.P. from the Watts Indicator Card and the ideal horse-power which would result if the engine followed the Rankine cycle. See section 102.

In Fig. 48 we have an ideal indicator card according to the Rankine cycle. Steam is admitted to the cylinder at a temperature T_1 for the part of the stroke represented by AB . It is expanded adiabatically to T_2 during the part of the stroke represented by BC . At the temperature T_2 the engine exhausts the steam against the back pressure represented by P_3 . The condition of the steam when

taken into the cylinder is represented by a temperature T_1 , pressure P_1 , and the volume V_1 . The condition of the steam when it is exhausted into the condenser is represented by T_2 , V_3 , and P_3 . T_2 is also the temperature of the condenser. If the extremely small amount of work required to return the water from the condenser to the boiler is neglected, the efficiency of this operation is expressed by the formula,

$$\frac{H_1 - H_2}{H_1},$$

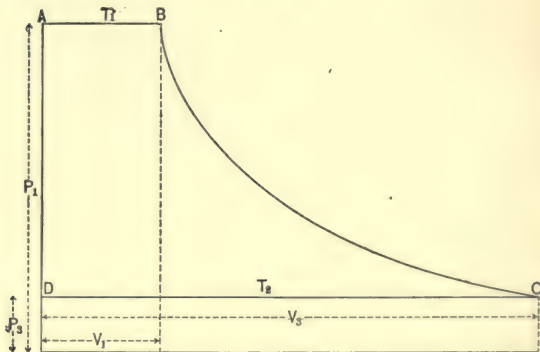


FIG. 48.—Ideal Indicator Card Following Rankine Cycle.

where H_1 is the total heat energy in the admitted steam and H_2 is the total heat energy in the steam returned to the condenser. Practically, however, the H_1 should be defined as the heat energy per pound added by the steam boiler and the H_2 as the portion of H_1 which is rejected to the condenser, if the above formula is to give the efficiency of a perfect steam engine using the steam as received and delivered.

If an engine drew a charge of a perfect gas at T_1° absolute, that charge would have an amount of heat represented by KT_1° , where K depends upon the weight of the charge and the specific heat, which are assumed to remain unchanged during the computation. Similarly, it would reject an amount of heat energy equal to KT_2° if T_2° is the temperature of the exhaust. The energy left in the cylinder equals $KT_1^\circ - KT_2^\circ$ and the efficiency is the useful energy (energy left in the cylinder) divided by the total energy taken in, or

$$\frac{KT_1^\circ - KT_2^\circ}{KT_1^\circ}.$$

Dividing both numerator and denominator by K , we have

$$\text{Efficiency} = \frac{T_1^\circ - T_2^\circ}{T_1^\circ}.$$

The ideal efficiency would be reached when adiabatic expansion took place in the cylinder of the engine and the gas gave up as much energy as it would receive when undergoing adiabatic compression.

If it is assumed that a perfect gas is used as a medium in a cycle similar to Rankine's, the same formula will express the efficiency of a perfect heat engine. If the specific heat of the gas is assumed to be constant the total heat factors H_1 and H_2 are in direct proportion to the absolute temperatures T_1 and T_2 of the gas. By comparing Figs. 56 and 57 with Fig. 48, the student will see the marked difference which exists between cards which are taken from an actual engine and an ideal card following the Rankine cycle.

REVIEW PROBLEMS, CHAPTER VI

38. In Fig. 30 what per cent of moisture must have been required per H.P. hour? (assume no losses except those shown).

39. If in Problem 38 the steam had been exhausted into the condenser dry, if there had been no other losses than those shown, and if dry saturated steam had been used, how much steam would have been required per H.P. hour?

40. An engine uses 25 lbs. of steam per H.P. hour. The steam is under 100 lbs. gauge pressure; quality of steam 990; and steam is exhausted into the atmosphere. Assume no losses or excess back pressure. What per cent of moisture must there be in the exhaust?

41. What per cent of energy entering the engine of Fig. 62 appears as useful work?

42. What per cent of the energy in the coal is turned into useful mechanical energy by the plant under discussion in Fig. 62?

43. What per cent of energy available for the boiler and furnace was not wasted in Fig. 62?

44. A boiler receives 5200 B.T.U's. per minute through every square feet of its firebox surface, which contains 54 sq.ft. If the boiler temperature is 287° F., and is fed with condenser water at 120° F., what weight of dry steam could be drawn off per hour?

45. If a certain boiler vaporizes 30 lbs. of water per hour from a feed-water temperature of 100° F., into steam at 70 lbs. gauge pressure for every boiler horse-power of its rating, what per cent of this heat in the boiler does the rating assume to be available for useful work (i.e., what per cent engine efficiency does this ratio assume)?

46. Given an amount of heat energy equal to that entering the boiler in Problem 45, how many pounds of water per horse-power would be vaporized per hour from a feed-water temperature of 212° F., into steam at 14.7 lbs. pressure?

47. How many pounds of coal per rated boiler horse-power hour would be required by boiler in Problem 45, assuming 75 per cent of the heat given off by burning coal goes into the water?

48. Having given the temperature of injection, discharge, hot well, and exhaust steam, as 50° , 100° , 120° , and 150° F., respect-

ively, calculate the weight of water required to condense 1 lb. of steam.

49. If the temperature of the injection is 70°F. , in Problem 48, how much water is required?

50. 350 lbs. of coal are burned on a boiler grate per hour and 3000 lbs. of water are passed through the economizer, the temperature of the water being raised 150°F. , and the temperature of the waste gases being lowered 300°F. If the specific heat of the flue gases is .24, what weight of furnace gases are produced per pound of coal burned?

51. An engine indicates 250 H.P. with a steam consumption of 18 lbs. per I.H.P. per hour. Having given the following temperatures, calculate the weight of injection water delivered for each double stroke of the circulating pump, which is making 200 R.P.M.

Temperatures of injection, discharge, hot well, and exhaust steam, 55° , 110° , 125° , and 138°F. , respectively.

52. If 25 lbs. of circulating water are required for each pound of exhaust steam condensed, and the temperature of the circulating water in passing through the tubes is increased from 56° to 98°F. , calculate the temperature of the exhaust steam when the temperature of the hot well is 108°F.

53. An engine indicated 74 H.P. and the heat entering the engine per minute to produce this power was 24,300 B.T.U's. Calculate (a) the heat equivalent of the I.H.P., (b) the heat admitted to the engine per H.P., (c) the ratio of the heat equivalent of the I.H.P. to the total heat admitted to the engine. How do you account for the difference between the heat admitted and the heat equivalent of the I.H.P.?

54. A steam-generating plant uses $2\frac{1}{2}$ lbs. of coal per I.H.P. per hour. If the heat value of each pound of coal is 13,500 B.T.U's., what is the ratio of the heat utilized as work on the pistons to the heat energy of the fuel producing that work? Why are the two quantities not equal?

55. The temperature of the injection is 50° and of the discharge 102°F. Calculate the temperature of the discharge if the temperature of the injection is increased to 60°F. , and if the weight of injection is increased by 15 per cent.

NOTE. Weight of injection $\times$ rise in temperature = constant.

56. A boiler evaporates 28,930 lbs. of feed water from a temperature of 127° into steam at 65 lbs. pressure during a run of 10 hours. What H.P. is developed by the boiler if rating is based upon the same assumed efficiencies as in Problems 45 and 46?

57. A compound engine and dynamo, direct coupled, gave the following results:

I.H.P.....	15	23	37	48	62
Output (Kw.).....	5.4	8.8	16	22.5	31
Total steam per hr. (lbs.)..	435	580	822	1025	1290

Plot the above output and steam used to a base of I.H.P. and add curves showing:

(a) Mechanical efficiency of combined plant = $\frac{\text{Electrical H.P.}}{\text{Indicated H.P.}}$

(b) Steam used per I.H.P. per hour.

(c) Steam used per Kw. hour.

58. Find the fuel cost of generating electricity per Kw. hr., from the above curves, if the average output be 25 Kw., the boiler using coal at \$4.25 per ton and evaporating $6\frac{1}{2}$ lbs. of water per pound of coal.

59. How many pounds of water could be evaporated from and at 212° by a boiler and furnace of 70 per cent efficiency by the coal of sample 14, Table IV?

60. How many pounds of water could be evaporated from a feed-water temperature of 80° F. to steam at 120 lbs. gauge?

61. How many pounds of feed water could be heated in an open feed-water heater from 60° F. to 200° F. by a pound of exhaust steam of a quality of .850 at atmospheric pressure?

62. How many pounds of exhaust steam would be required to heat a ton of feed water in an open heater from 70° to 180° F. if 895 quality of steam at 16 lbs. was used?

63. How many pounds of water per pound of combustible will be evaporated in Prob. 59?

64. A boiler plant evaporates 6 lbs. of water per pound of coal without an economizer. The steam pressure is 150 lbs.; feed temperature, 120°. By adding an economizer the feed temperature is increased to 230°. If the same quantity of heat is delivered to the boiler when the economizer is used, what is the increase in the plant efficiency?

65. If the coal used in the previous problem contained 13,600 B.T.U., what was the percentage efficiency both with and without the economizer?

66. An engine uses 24 lbs. of steam per I.H.P. per hour. Feed temperature, 120°; steam pressure, 135 lbs. The boiler evaporates 8.8 lbs. of water from and at 212° F. per pound of coal. How many pounds of coal are required per I.H.P. per hour?

67. A boiler evaporates 8.6 lbs. of water per pound of coal. Steam pressure, 125 lbs.; feed temperature, 150° . What weight of water per lb. of coal will it evaporate with a steam pressure of 5 lbs. and a feed temperature of 180° ?

68. A boiler evaporates 8000 lbs. of water per ton of coal. Steam pressure, 180 lbs.; feed temperature, 50° . What will it evaporate if the steam pressure is 200 lbs. and the feed temperature is 150° ?

69. A coal contains C, 78 per cent; H, 6 per cent; O, 3 per cent. Efficiency of the boiler and grate, 70 per cent; feed temperature, 180° ; steam pressure, 150 lbs. absolute. Steam contains 2.2 per cent moisture. In the previous problem what is the equivalent evaporation? What is the actual evaporation per pound of coal? What is the equivalent evaporation from and at 212° per pound of coal?

70. A boiler is reported to evaporate 12.5 lbs. of water per pound of coal. Coal contains 13,400 B.T.U. and uses 20 lbs. of air per pound to burn it. Temperature of the boiler room, 70° . Compute the percentage efficiency of this plant.

71. In Fig. 37 we have accounted for the work done in raising the load vertically. Suppose that 75 per cent of the engine's output was consumed while the load was being raised vertically and that an additional 25 per cent was used while the load was being moved horizontally. Reconstruct the energy diagram, distributing the losses to furnace, boiler, and engine in the same proportion as in Fig. 37.

SUMMARY, CHAPTER VI

A SIMPLE STEAM-POWER PLANT contains only three members: furnace, boiler, and engine. There are three currents which must be traced through the plant: the air and flue gas circuit, the water circulation, and the energy stream. Large steam-power plants introduce other members when by so doing a reduction of cost efficiency (See page 178) will result. Such members are introduced to reduce the energy losses.

A STEAM BOILER takes a small volume of water and by heating it up delivers it as steam at the same pressure as taken in, but with a greatly increased volume.

THE TRUE EFFICIENCY of a Steam Boiler is not often computed. Results which are labeled "Boiler Efficiency" are usually the joint efficiency of the boiler and furnace. Efficiency of the boiler unit is expressed in a variety of ways.

Factor of Evaporation =

$$\frac{\text{Total heat of steam} - \text{Total heat in feed water}}{970}$$

Water Rate = pounds of steam and water per I.H.P. hour.

THE ECONOMIZER warms the feed water and derives its heat from the hot flue gases as they leave the boiler on their way to the chimney.

THE FEED-WATER HEATER warms the feed water and derives its heat from the hot steam exhausted by either the main engine or the auxiliaries or both.

THE BAROMETRIC CONDENSER reduces the back pressure on the engine by liquefying the steam through contact with a steady stream of cool water.

THE SURFACE CONDENSER accomplishes the same result without mixing the steam with the circulating water.

THE STEAM ENGINE moves because of the difference of pressure upon the two sides of the piston head.

M.E.P. for a stroke is the average difference in pressure on the two sides of a piston during that whole stroke.

At the same pressures, the distance the piston moves depends upon the volume of steam supplied.

The WORK Done per Stroke = $\text{Area} \times \text{M.E.P.} \times \text{Length of Stroke}$. (Notice how this computation is made from the steam indicator card. See section 102).

There are usually two working strokes per revolution, and for each

$$\text{I.H.P.} = \frac{\text{M.E.P.} \times A \times N \times L}{33000}.$$

The total I.H.P. is the sum of the I.H.P. for each stroke.

THE RANKINE CYCLE states the theoretical correct behavior of steam in an ideal engine. The formula to express the efficiency of an engine working on this cycle is

$$\text{Eff.} = \frac{H_1 - H_2}{H_1}.$$

For all-gas cycle, we would have under ideal conditions

$$\text{Eff.} = \frac{T_1 - T_2}{T_1}.$$

CHAPTER VII

FUNCTION OF GAS POWER PLANTS

60. Comparative Efficiency. From the last chapter, it appears that in the very best modern steam plants only about a sixth of the heat energy in the fuel is converted into mechanical energy; 20 per cent is usually fixed as the practical limit of efficiency for steam power plants. The large amount of heat energy of vaporization which must be lost in the exhaust of the steam engine limits the efficiency of the typical arrangement shown in Figs. 38 and 39. Higher efficiencies have been sought, therefore, in a different type of engine.

The perfection of the explosion type of engine has progressed to a point where it is successfully competing with the steam engine in many industries. The gas engine has been particularly successful in small installations and in motor vehicle work. It has shown greater efficiency from an *energy efficiency* standpoint in practically every field. However, when the cost of fuel, labor, maintenance, depreciation, etc., is considered, the "*Cost Efficiency*" is not so certainly in favor of the explosion type of engine.

By "*Cost Efficiency*" is meant the *H.P. hours per dollar* expended for fuel, labor, overhead charges, etc.

61. Fuel. The explosion engine is always a "gas" engine, though gas power plants are run with every type of coal, all grades of oil, and all of the various kinds of gas fuels. In the case of coals and oil there must be some means provided to change the fuel to a gas and to mix it with air (containing the oxygen to support the combustion)

before attempting to explode the mixture in the cylinder of the engine.

The **carbureter** (for light oils) or the **vaporizer** (for heavy oils) is used to evaporate the liquid and to mix the gas with the proper proportion of air before admitting the fuel to the cylinder.

The Diesel, the Mietz & Weiss, and all of the other so-called oil engines which inject liquid fuel into the cylinder, depend upon some means of spraying the liquid and some method of maintaining a temperature in the cylinder which will vaporize the fuel and will cause combustion at the proper time. (See discussion, p. 29.)

62. Firing. The explosion must occur at a very definite position of the piston to give the best results and an ignition system adapted to the type of engine used and to the fuel is necessary.

Most engines are fired by an electric spark. The various so-called electrical ignition systems all fall under the two general classifications: **JUMP-SPARK** (or high-tension system) and **MAKE-AND-BREAK** (or low-tension system). **HOT BALL** and **HOT TUBE** ignition systems are also used. The Mietz & Weiss engine described on p. 181 illustrates this latter type of system.

The jump-spark systems all use a spark plug in the cylinder. The plug has two pointed terminals inside the cylinder connected to a source of potential and a high voltage causes a spark to jump from one terminal to the other and thus ignites the gas.

The make-and-break systems all require a finger inside the cylinder. This finger moves forward and makes contact with the wall of the cylinder. Then, at the exact instant when an explosion is desired, the finger is made to move away quickly. This breaks the mechanical contact of the surfaces. The effect is to break the electrical circuit, and spin out an arc. This finger is usually operated from a cam on the main shaft.

These systems differ only in the details of the arrangement of the various essential parts. The electrical theory upon which each depends will be found in electrical text books.

63. Cycles. The term cycle, when applied to gas engines, does not differ essentially from its meaning as stated in the previous chapter. It should simply be remembered that the exploded gases are not used over again in the cylinder as in the case of steam, but are exhausted into the air.

The time of mixing the fuel with the gases which are to supply the oxygen differs in the various types of engines, and these differences have resulted in such terms as "Otto Cycle," "Diesel Cycle," etc.

The chief basis of classification of engines as to cycles depends upon the number of strokes of the engine per explosion. The *two-cycle* engine gives an explosion every revolution of the crank shaft, or one explosion for every two strokes. The *four-cycle* engines give an explosion during each alternate revolution of the crank shaft, or one explosion for every four strokes.

The *characteristic of design* which has tended to make the two-cycle engine so simple is illustrated by Fig. 49. This feature is the complete absence of valves in the cylinder. By using an enclosed crank case a mixture of air and fuel may be sucked into the crank case during the "idle stroke" by the partial vacuum produced by the piston moving out away from the crank shaft. The opening marked "suction port" in the figure may be connected to a carbureter when gasoline is used. When the piston moves forward on the "working stroke" the charge in the crank case is compressed. The exhaust port is uncovered before the admission air port is uncovered. The pressure in the cylinder falls to nearly that of the atmosphere before admission takes place and therefore the compressed charge in the crank case comes in with a rush and sweeps out through the exhaust port the burned gases produced by the explosion. When the stroke has progressed to a point where the air port is uncovered the charge is by-passed through 134 into the cylinder. On the piston head is a projection which deflects the air upward into the cylinder and away from the exhaust port. As the piston moves back on its "return

stroke" the charge is compressed and finally exploded as the engine passes dead center. The cycle of events is complete and is repeated indefinitely.

The engine shown has special features of construction to permit liquid fuel to be used. Fuel is injected just before the engine reaches dead center by the pump 40, operated from the crank shaft. Only air therefore is compressed in the crank case. 64 is a hot ball in an enclosed insulated chamber. To start the engine this is heated, with

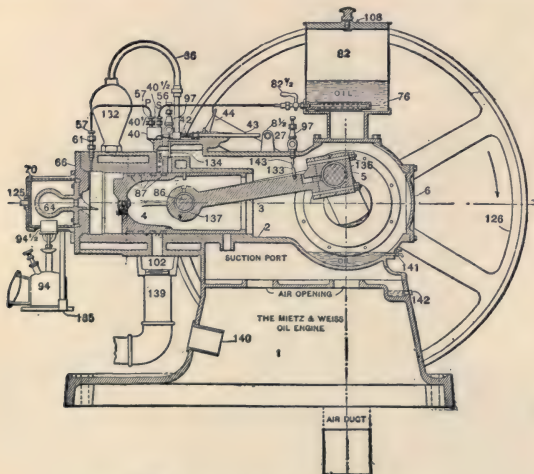


FIG. 49.—Mietz & Weiss Two-Cycle Engine.

a torch, 94, to a red heat. When the fuel is injected by the pump 40 it impinges upon the spoon-like projection of 64, which is red hot. It is at once vaporized by this heat, and mixed with the air. It is exploded by the heat of compression. The fuel is pumped at the proper time in the stroke by the governing device 27, hitting the piston rod extension of pump 43.

The four-cycle engine is more complicated and always has valves which are operated usually from a counter shaft. This is frequently called the cam shaft or half-speed shaft. Poppet valves are almost

always used. In Fig. 50 an Otto four-cycle engine is shown. Fig. 51 shows a section through the cylinder head and valve mechanism. The charge enters the cylinder through the poppet valve *A*. The valve stem *C* is operated from the shaft which carries the inlet cam *H* through *G*, *E*, and *D*. *M*, on the same shaft, operates the exhaust valve *I* through the stem *K* and the arm *L*.



FIG. 50.—Otto Four-cycle Engine.

S is a make-and-break igniter which is energized from the oscillating magneto. The mechanism by which this is operated is not shown in the cut.

64. Fuel Circulation in a Producer Gas Power Plant.

A producer gas power plant may be divided into two parts

for purposes of discussion. First, a gas-producing, cleansing and storage system, and second, an explosion engine or motor as it is often called. The gas-producing part of the

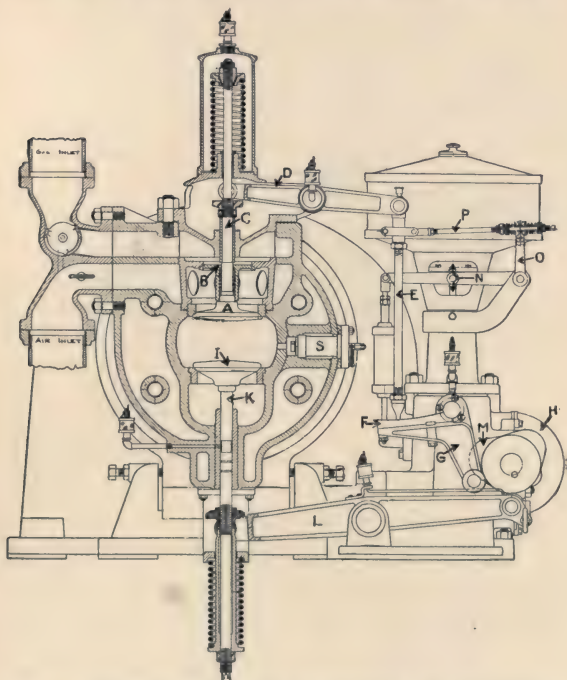


FIG. 51.—Sectional View of Valve Mechanism of the Otto Engine.

plant may equally well provide producer gas to run a furnace or for any purpose for which a fuel gas may be used. The engine may be similar to the Otto engine just described or any other designed to use a gas fuel of this general character.

Because of limited space, only one gas power plant can receive detailed attention in this book. A suction gas producer plant has been selected for study and the arrangement of its members is shown in Fig. 53. Fig. 54 shows the energy circulation through this plant.

The drawings for Figs. 53, 54, 63 and 64 were made by students of the Applied Chemistry Class of 1913 as optional problems. Figs. 53 and 54 are for a plant similar

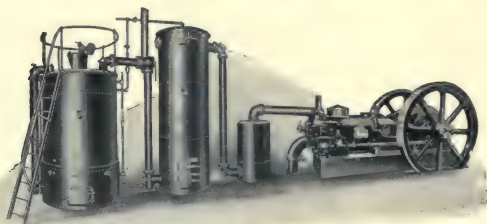


FIG. 52.—Suction Producer Plant with Otto Engine.

to that shown in Fig. 52 except that they have two additional features, as will appear presently.

Producer gas plants may be designed to burn any type of coal, and it is usual to construct them to burn the coal which is cheapest in the town where they are to be used. They are particularly efficient from a "Cost Efficiency" standpoint when using certain low-grade coals.

The chemical action that takes place in the various types of gas producer is essentially the same. In the gas producer, or generator, shown, coal is fed in at the top, and the hot gases coming through the fuel bed heat up the fresh coal. Because of this heating, the volatile matter is first driven off, then carried through the various members of the plant and finally delivered to the engine cylinder. Then as the coal settles it becomes white hot, and at that temperature it is very eager to unite with oxygen. This affinity for oxygen is so strong that any gaseous carbon atom which has taken on *two* atoms of oxygen and is rising through the fuel bed as CO_2 is readily reduced, i.e., made to give up one O by a second carbon atom, and two molecules of CO

pass on to the engine. As the coal drops down still further, the incoming stream of air is richer in oxygen and the remaining coal burns to CO_2 and supplies the heat to keep the process going.

With the air, a small amount of steam is often supplied, partly to prevent clinkers forming and partly to supply the incandescent coal with another molecule containing oxygen which the carbon can take over. The water, H_2O , is broken down into hydrogen, H , which is very combustible, and oxygen, O , which at once unites with the carbon in the coal to form CO . For each pound of H_2O broken down 1873 B.T.U. must be taken from the fire. When the H from this H_2O is burned in the cylinder this *same* amount of energy is returned as heat.

The principal differences between the various types of generators used in producer gas plants occur in the percentages of H_2O (steam) used and the treatment of the volatile matter.

The gases, as they rise from the top of the coal, in a producer gas plant, contain elements and compounds from the coal such as CO , H , O , and N (nitrogen). The nitrogen was in the air and has not been changed in chemical composition. Some idea of the relative per cent of each of these gases present may be gained by referring to Table V, Nos. 1, 8 and 9.

These gases are very hot. They are first shown to pass through an economizer in which they give up some of their heat to the air which is being supplied to the producer. Next they pass into a boiler which supplies the steam which is fed to the producer.

From the boiler, they pass into the scrubber, where all dust, ammonia and tarry volatile substances are deposited. As they pass upward through the wet coke which nearly fills the scrubber, they are cooled to the water temperature, which causes the less volatile products to change to a liquid which is deposited on the coke.

A storage tank receives the gases coming from the scrubber. This tank is merely large enough to prevent a sudden rush of gas through the apparatus when the engine is sucking a charge, and a later halting of the flow after the admission valve closes. It equalizes the pressure through the scrubber and producer and makes their action more certain and uniform.

64A. Fuel Combustion. Whether the source of the gas supplying energy to an engine is a gas producer, a public gas plant, a natural gas well, or a vaporizer, *it must be mixed with a proper amount of air* (to obtain oxygen) before it will burn in the cylinder. The air and gas are drawn into the engine through suitable mixing valves and there

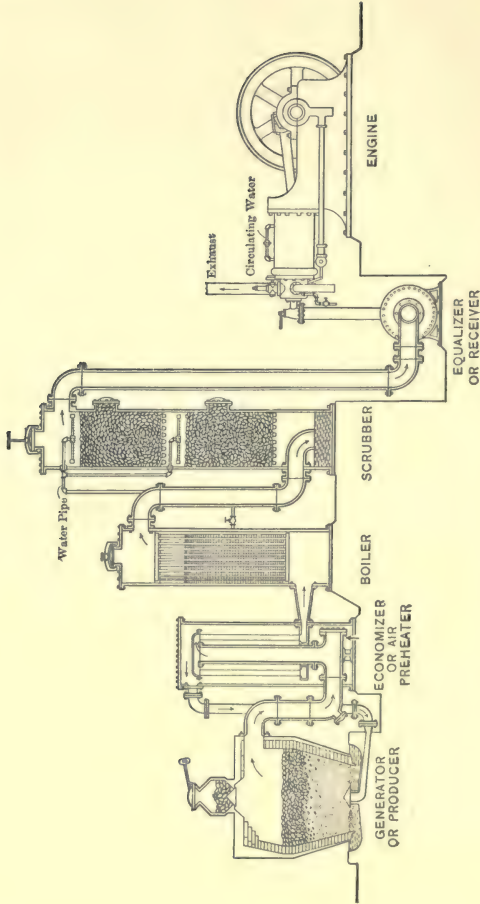


FIG. 53.—Section of Typical Producer Suction, Gas Power Plant.

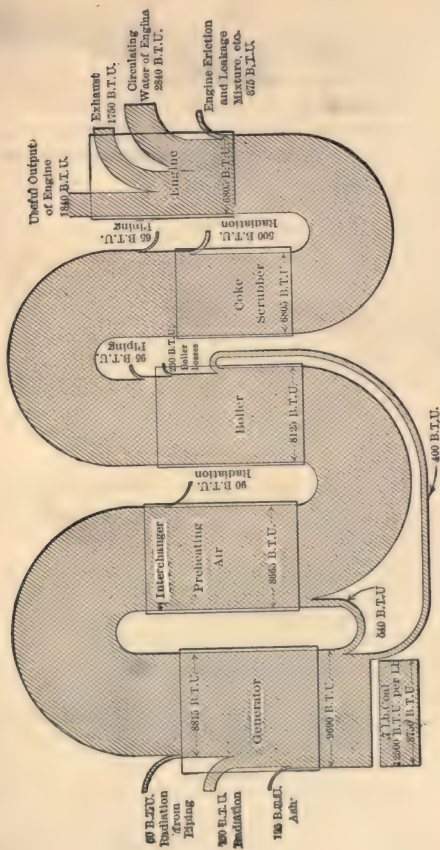


Fig. 54.—Energy Diagram for Plant Shown in Fig. 53.

exploded by an electric spark at the proper time. The high pressure produced by the explosion moves the piston out and useful work is done by the expanding gases. Thus it follows that the principle of operation of the explosion engine is very similar to that in a steam engine. The working medium is under high pressure during the early part of the working stroke and expands nearly adiabatically during the remainder of the stroke. The I.H.P. of a gas engine may be obtained in exactly the same way as I.H.P. of a steam engine (see p. 151). The mean effective pressure is computed from an indicator diagram obtained by using a Watts indicator in exactly the same way as with the steam engine. (See Section 102.)

These gases are very hot and tend to heat the walls of the cylinder and the piston. The temperature of the gases at the explosion is high enough to melt the iron in the cylinder. To have satisfactory lubrication the metal parts must be kept cool, and for this purpose water is usually circulated through a jacket placed about the cylinder. In large engines the cylinder head and the piston are water cooled as well. This water carries away much of the heat energy of the fuel, and inevitably decreases the efficiency of the engine.

When the exhaust port opens, the pressure is still above that of the atmosphere and when the gases leave the cylinder they are still very hot. Consequently, much of the heat energy in the fuel is lost in the exhaust.

65. Energy Circulation. In the energy diagram, Fig. 54, the flow of heat energy through this system is shown. In a complete energy cycle there are, at the start, three sources of energy. The primary source is .7 lb. of coal, which contains 8750 B.T.U. of heat energy. Returning from a previous cycle, 540 B.T.U. are brought back in "sensible" heat by the preheated air supply. In the same way 400 B.T.U. more than were in the water at atmospheric temperature are returned in the live steam supply.

The figure also shows the losses. In the generator they are due to radiation and ash. The losses in the air heaters are due to radiation. 540 B.T.U. are shown to be credited to the interchanger. 400 B.T.U. are credited to the boiler, because of the energy returned in the live steam to the generator. 260 B.T.U. are lost in the boiler due to radiation, leakage, steam used for other service purposes, etc. Piping is also charged with radiation losses. The scrubber loses 500 B.T.U., some of which is due to radiation, but a larger part is due to the cooling effect of the water. As the gases rise from the coal in the generator they have a temperature which probably exceeds 1500° F. While the gases are in contact with the water they are cooled to the temperature of the water and consequently give up heat. In the engine there is a friction leakage, and fuel waste of 375 B.T.U. To cool the cylinder, water is circulated in a jacket and the water takes away 2804 B.T.U. In the exhaust 1750 B.T.U. are lost in the sensible heat of the gases. 1840 B.T.U. appear as B.H.P. hour useful work.

The scientific way to express the efficiency of a producer gas power plant is to give the per cent of the available energy in the coal that is delivered by the engine in the form of useful work. The efficiency of the gas-producing equipment is the B.T.U. fuel value in the gas as it leaves the scrubber divided by the total B.T.U. in the coal from which the gas was produced. This is usually given in per cent. The efficiency of the engine is the useful energy delivered, divided by the energy in the gas supplied to the engine as fuel. This ratio is usually given in per cent.

Problem 1. What was the efficiency of the engine in Fig. 53?

Problem 2. What was the weight of coal required per H.P. hour by the plant of Fig. 53?

Problem 3. What was the over-all plant efficiency of Fig. 53?

Problem 4. What was the efficiency of the gas generating equipment in Fig. 53?

Problem 5. What per cent of the energy delivered to the engine was lost in the exhaust?

Problem 6. What per cent of the energy delivered to the engine was taken away by the circulating water?

Problem 7. If 6 lbs. of air by weight were used per pound of coal what was the amount of preheating?

Problem 8. If the atmospheric temperature and feed-water temperature are the same, and the pressure of the steam 5.3 lbs. gauge, what weight of steam was added for each .7 lb. of coal?

Problem 9. If there was an equal weight of air mixed with the gas before explosion, bearing in mind the conditions mentioned in Probs. 7 and 8, compute the temperature of the exhaust gases. (Assume the specific heat of the gases to be the same as air.)

Problem 10. What must have been the temperature immediately after the explosion in the cylinder, assuming all of the conditions to hold as in Probs. 7, 8, and 9. The engine has 25 per cent clearance and combustion is completed while engine is still on dead center.

NOTE. It is not true that the specific heat is constant under all the conditions mentioned, but for the purposes of these problems it will do to use the value given in Table VI for air.

Problem 11. There is a theory that the ideal efficiency of a heat engine is expressed by the following ratio where the temperatures are absolute, and T_1 equals the temperature of charge after explosion and T_2 equals the temperature of exhaust.

$$\frac{T_1 - T_2}{T_2} = \text{Eff.}$$

How nearly does it agree with your computed results in the previous problems?

Problem 12. Draw an energy diagram showing 1 H.P. hour of useful work output for a liquid fuel used in an explosion engine. The efficiency of the engine is 28 per cent. Loss in cooling water and radiation is 40 per cent. Two per cent of energy is lost in vaporizing the liquid and in leakage, 30 per cent is lost in the exhaust. There are 19,000 B.T.U. per pound in the fuel.

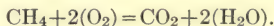
66. Explosive Mixtures. The relative weights of fuel and air which must be used to produce complete combustion may be computed from the information given in Chapter II. It may be possible to produce an explosion if the mixture deviates from this theoretical amount. How great a deviation from the ideal proportion is allowable is dependent upon the construction of the engine and the type of fuel. Allen and Bursley state that the per cent by volume of fuel which when mixed with air will explode, varies from 16 to 74 per cent for CO, from 8 to 17 per cent for illuminating gas, and from $2\frac{1}{2}$ to 5 per cent for gasoline. The most economical results will be obtained with mixtures containing less than the *theoretical* amount of fuel.

To operate any explosion engine below full load, some method of governing is necessary. Stationary engines are often governed by the "hit or miss" method. With this method fuel is admitted to the cylinder only at such times as the speed is below a certain maximum. This method is economical, but results in a very irregular speed. Governing is more often produced by throttling. By this means the amount of fuel is reduced and the engine is "starved." Economical results follow at light loads. When the throttle is operated by hand, as in the gasoline automobile engine, the range of speeds obtainable is not low enough at no load. Further control is obtained by adjusting the time of a spark. Those devices are most economical which control the gas supply and never allow the mixture to exceed the theoretical per cent of fuel. At the same time they should not reduce the fuel per cent far below the theoretical value.

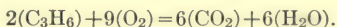
The theoretical per cent of air required for complete combustion may be computed in a much simpler manner than in Chapter II when the analysis is by volume. The computation for a sample of illuminating gas follows:

Gas Contained.	Per Cent by Volume.	Volume of Oxygen in Per Cent of Total Volume of Coal Gas.
Hydrogen (H ₂).....	48	24
Marsh gas (CH ₄).....	39.5	79
Illuminants (C _n H _{2n}).....	3.8	17.1
Carbon monoxide (CO).....	7.5	3.7
Nitrogen.....	0.5	
Oxygen.....	0.7	-0.7
	100	123.1

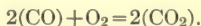
The values of the second column are obtained as follows: It is known that two volumes of hydrogen unite with one of oxygen to form water and the accepted chemical formula is $2(\text{H}_2) + \text{O}_2 = 2(\text{H}_2\text{O})$. Therefore half as much oxygen by volume as hydrogen is required. Similarly one volume of CH₄ unites with two volumes of oxygen according to the formula:



Therefore the volume of oxygen given in the table is twice as great as that of the CH₄. Likewise if *n* equals 3 the illuminants would then be exclusively C₃H₆. This is assumed and the reaction would then be:



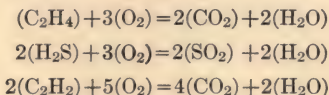
Thus $4\frac{1}{2}$ volumes of oxygen would be required for each volume of C₃H₆. Finally two volumes of CO unite with one volume of O₂ to make CO₂ according to the formula:



Therefore only half as much oxygen as carbon monoxide is required.

By adding algebraically the per cents of oxygen it is found that for 100 parts of gas 123.1 parts of oxygen would be required. Since there are 20.7 volumes of oxygen in 100 volumes of air, to obtain 1.23 volumes of oxygen will require that 5.95 volumes of air be injected into the cylinder.

The combining volumes of the other compounds mentioned in Table V may be obtained from the chemical formulas which show how they combine with oxygen. These formulas follow:



In all of the above computations it must be understood that all of the gases are at the same standard temperature. For a detailed statement covering other compounds, and more complicated conditions, the student is referred to works on chemistry.

Problem 13. What would be the theoretical volume of air required for each volume of gas in analysis 1, Table V?

Problem 14. How much air would be required to burn sample 2, Table V?

Problem 15. If an engine operated with the conditions of combustion as in Prob. 13, and if 25 per cent of the energy in the fuel was carried from the engine in the exhaust gases, what was the temperature of the exhaust as it passed into the atmosphere. (Assume atmospheric pressure, a specific heat the same as for air, no velocity effect and a normal temperature of the air of 70° F.)

Problem 16. What per cent of the heat energy lost in the exhaust was carried away by the inert nitrogen in Prob. 13?

Problem 17. Compute the volume of air to completely burn one cubic foot of CO.

Problem 18. If in Fig. 39, 12 lbs. of air were required per pound of coal, what was the stack temperature? What per cent of the energy lost was due to the heat in the inert nitrogen as it passed up the stack?

67. Working Medium. In texts upon heat engines the substances used in the cylinder to exert a pressure against the piston are called the *working medium*.

In the steam power plant we use water as a working medium and supply energy to it outside the cylinder in a boiler. We have already seen the low efficiency which must follow the use of water for this purpose.

In the gas engine we always use as our working medium the products of combustion of our fuel. In all engines, so far used commercially, the combustion takes place in the cylinder itself. From the preceding problems it is seen that about 70 per cent of this working medium is nitrogen, which simply serves to dilute the products of combustion of the fuel. The inevitable losses in both the steam plant and the gas power plant from handling this large weight of waste material are very large.

The theoretically correct solution of the problem of economically utilizing fuels will doubtless be obtained through the perfection of some one of the many schemes for burning the fuel outside the engine and then expanding the gaseous products of combustion in a suitable engine or turbine until their temperature and total energy do not greatly exceed the energy in the gases of the atmosphere. Many such experimental plants have been devised and patented, but none have come into commercial use. Models have shown better efficiency than any commercial plant now in use, but it has not been possible to find materials which, without deterioration, would stand the temperatures required.

REVIEW PROBLEMS, CHAPTER VII

19. A gasoline engine uses 1.2 lbs. of oil, containing 18,200 B.T.U., per brake horse-power per hour. It is assumed that the losses are as follows:

- 2 per cent of the total loss is friction;
- 3 per cent is unburned fuel;
- 40 per cent is thrown out in the exhaust;
- 55 per cent is carried away in the jacket water.

Draw energy diagram for this engine.

20. What is the heat efficiency of this engine?

21. What is the oil consumption per I.H.P. of the engine in Prob. 19?

22. If this is a single-cylinder four-cycle engine, making 1200 r.p.m., delivering 16 H.P., having an 8-in. stroke, and a piston area of 20 sq.ins., what is its M.E.P.?

23. A gas engine uses 20 cu.ft. of gas per horse-power per hour. Each cubic foot of gas contains 550 B.T.U. The initial temperature in the engine is 2100° F., and the final temperature is 850° F. What is the ideal efficiency? See Problem 11.

24. What is the heat efficiency of the engine in Prob. 23?

25. An engine has an 8-inch stroke and 24 sq.ins. piston area. It is two cycle and running at 300 r.p.m. Its M.E.P. is 80 lbs. It exerts a force of 21 lbs. at a radius of 66 ins. What is the force of energy lost in friction? Comment on the probable mechanical condition of this engine.

26. A gas-engine cylinder is 9 ins. diameter, its stroke 16 ins., mean pressure 75 lbs. per square inch, revolutions 180, explosions 85, diameter of flywheel 5 ft., friction of brake band 160 lbs., gas used per hour 250 cu.ft. of a thermal value of 600 B.T.U. per cubic foot. Find the I.H.P., B.H.P., thermal efficiency, and mechanical efficiency.

27. The cylinder of a four-cycle gas engine is 16 ins. in diameter, the stroke is 24 ins. Clearance is 20 per cent. Find:

1. (v_1) volume in cubic feet at end of admission stroke.
2. (v_2) volume in cubic feet at end of compression stroke.

28. Charge in above engine is taken in at 14.7 lbs. pressure and at 60° F. Find:

- (1) Weight of *charge* if 1 cu.ft. weighs .0087 lb. at 14.7 lbs. per square inch and 32° F.
- (2) Weight of entire mixture in cylinder at end of admission stroke.

29. If the pressure at end of compression stroke is 181 lbs. per square inch, what is the temperature?

30. If the charge consists of 1 part gas and 9 parts air, what is the temperature at end of explosion?

NOTE. Use *Heat of Combustion* as 600 B.T.U.'s per cubic foot of *gas* at end of admission. Use specific heat of air at constant *volume*.

31. What is the pressure at end of the explosion?

32. Assuming the pressure at end of explosion is 12.3 times as great as at end of expansion stroke, what is the pressure and temperature at end of expansion stroke?

33. If the engine makes 180 r.p.m., what horse-power does it develop? Assume an efficiency of 30 per cent.

SUMMARY, CHAPTER VII

GAS POWER PLANTS show greater thermal efficiency than steam power plants and frequently better cost efficiency. For small plants they are unquestionably superior to steam.

FUEL is either supplied to the cylinder, as a gas or is changed to a gas in the cylinder before combustion takes place.

FIRING is the term applied to the igniting of the fuel. It is accomplished in those engines in which electrical ignition is employed by either a make-and-break system or a jump spark system.

TWO-CYCLE and four-cycle usually refer to the number of strokes per explosion. Special cycle names are used to describe the method of introduction and the condition of the fuel when introduced.

GAS PRODUCERS are commonly used to supply fuel in the gaseous form, to an explosion engine from an original supply of coal. A Producer-Gas Power Plant is any combination of a gas producer and a gas engine.

EXPLOSIVE MIXTURES are usually quick burning, well-proportioned, intimate mixtures of a gaseous fuel and oxygen.

WORKING MEDIUM is an expression used to refer to the heat vehicle in an engine.

CHAPTER VIII

EXPANSION OF GASES (*Continued*)

THE most difficult heat theory for the student to understand and apply is that which explains the expansion of gases in cylinders of engines, compressors, etc. The complex conditions which exist, however, when analyzed step by step, become clear.

68. Specific Heat of a Gas. The first point to be noted is that a gas has two specific heats.

The specific heat at constant volume (C_v) of a gas is the heat energy required to raise the temperature of a unit mass of gas one degree without a change in volume.

The numerical value of the specific heat at constant volume is practically the same for air, oxygen, nitrogen, CO, CO₂, and mixtures found in gas engine cylinders at ordinary temperatures, but an appreciable difference from the values given in the table may be expected for large changes in temperature. When this value is expressed in B.T.U. per pound of gas, the value is numerically the same as when expressed in calories per gram.

When heat energy is added to a gas kept at constant volume, the temperature and pressure both increase. According to the Kinetic Theory, the heat energy increases the mean velocity of the molecules. The increased frequency with which they impinge against the side of the containing vessel as well as the increase of kinetic energy accounts for the increase in pressure on the sides of the vessel. The increase in temperature in the case of a "perfect gas" would be exactly in proportion to the amount of energy added. The heat capacity or specific heat of a gas at

constant volume is a definite quantity for any gas for any fixed range of temperature.

Table VI gives a set of values for the specific heat of gases at constant volume, and in each case gives the range of temperature over which the value given is an average.

The Specific Heat at constant pressure (C_p) of a gas is the heat energy necessary to increase the temperature of a unit mass one degree without a change of pressure.

These definitions are simple enough, and the fact that there are two specific heats is easily explained. If a gas is heated at constant volume all of the energy added goes into internal energy of the gas, or, in other words, all of the work tends to produce a rise in temperature. If heat energy is added at a constant pressure, however, the gas will increase in volume while its temperature is increasing one degree. For an increase in volume to take place the atmosphere or other restraining body must be pushed back, and consequently work must be done against the opposing pressure which this body is exerting. This work is external and does not heat the gas. Thus, just as in the case of latent heat, we may analyze C_p into internal and external heat energy. To illustrate:

Given 1 lb. of air at 32°F. , held in a cylindrical chamber, similar to that in Figs. 28 and 29, of 1 sq.ft. cross-section and indefinite length. If we expand it at a constant pressure of 14.7 lbs. per square inch to 33°F. we will increase its volume by $1/493$ of its original volume. Its original volume was 12.39 cu.ft. and, therefore, its increase in volume must have been $1/493 \times 12.39 = .0251$ cu.ft. To free this volume and make it available for occupancy, energy must have been supplied to move an area of 144 sq.in. through .0251 ft. against atmospheric pressure, or $(14.7 \times 144 \times .025) = 53.3$ ft.-lbs. of work must have been done. (See section 37: $R=53.3$.) In B.T.U. the work done was $53.3 \div 780 = .0683$ B.T.U. expended in doing external work.

In addition to doing the external work (C_e) .1694 B.T.U. energy is needed to heat the gas. .1694 B.T.U. (C_v) will raise one pound of air from 32°F. to 33°F. at constant volume. All of this .1694 B.T.U. is retained in the gas as heat (internal work).

If we add these two quantities of energy we have, .1694 B.T.U. (internal work) + .0683 B.T.U. (external work) = .2377 B.T.U. total heat energy required at constant pressure for this 1° F. rise.

By referring to Table VI for the specific heat of gases, the student will observe that the difference between the two specific heats given represents in each case the external work. It thus appears that the real heat capacity of the gas is expressed by the specific heat at constant volume.

When heat energy is added to a gas kept at constant pressure the volume and the temperature tend to increase. In this case some work must be done externally if the volume is increased against the atmospheric pressure. Also work must be done internally to produce the necessary increase in the mean velocity of the molecules which, according to the Kinetic Theory, we expect to take place. The specific heat at constant pressure is therefore greater than the specific heat at constant volume.

Now a cause of much confusion is the careless way in which some writers give the impression that the energy added at constant pressure is "in the gas." Though statements are worded loosely, the student should always remember that *some of the energy added to the gas in constant pressure expansion is used by the gas to do external work.*

Similarly the expression "total heat energy of steam" *does not mean that all of the B.T.U. are actually in the steam.* This expression really gives the number of B.T.U. required to produce the steam at this pressure from water at 32° . The number of B.T.U. *in the steam* is less than this value by an amount equal to the external work done during the production of the steam.

The specific heat of each gas is different from that of every other gas. In gas-engine computations and in computations involving flue gases or other mixtures of air and products of combustion, it is usual to take the specific heat, and any factors depending upon the specific heat,

as the same as for air. Notice that in Table VI the value for CO_2 falls far enough below that given for air, and that the value for N is enough above to give an average result equaling the value for air.

In the general formula, $PV = RT$ (see page 90), R for air equals .37 when V is expressed in cubic feet and P in pounds per square inch. If P is expressed in pounds per square foot, R for 1 lb. will equal $.37 \times 144$ (sq.in.) or 53.37. This value for R can also be obtained by expressing the values of the specific heat at constant pressure and at constant volume as shown in the following table:

Gas.		Value of Ratio from Table VI.	B.T.U. for 1 Pound Raised 1° F.	Foot-pounds. 1 Pound Raised 1° F.
AIR	C_p	.2375	.2375	184.77
	C_v	.1689	.1689	131.40
	$C_p - C_v$	.0686	.0686	53.37
AMMONIA	C_p	.5084	.5084	395.54
	C_v	.3500	.3500	272.30
	$C_p - C_v$	.1584	.1584	123.24

As a further illustration of how we select the proper specific heat for use in practical computations, the student should consider how we would find the energy required to superheat 10 lbs. of steam under atmospheric pressure from the boiling-point to 500° F. If we imagine that the steam is in the cylinder of Fig. 29 at 212° F. when the heat is applied, it will be clear that the addition of heat energy will tend to increase the volume and move the frictionless piston up. In this way the heat energy will do work against the atmosphere, and only part of the energy added will remain in the gas. The value in the column in the table marked C_p must therefore be used.

Accordingly, if we assume that the specific heat (C_p) is constant, .48 is the value to be used, and

$$.48 \times 10 \text{ lbs.} \times (500^\circ - 212^\circ) = 1380 \text{ B.T.U. of heat added.}$$

Problem 1. Compute the true specific heat of sample 10, Table V?

Problem 2. Compute the true specific heat of sample 11, Table V.

Problem 3. If CH_4 has a specific heat (C_p) of .593, compute the specific heat of sample 8, Table V.

Problem 4. If in a gas engine a charge weighing .2 lb., is at 120 lbs. pressure and at 400° F. , what would be its temperature after the explosion of the gas if 25 B.T.U. are released? (Take value of specific heat as given in table. Assume no change in volume.)

Problem 5. Make a tenth column in Table VI and compute and enter in it the value of R for 1 lb. of each gas.

69. Isothermal Expansion. The word isothermal means "at equal temperatures," and isothermal expansion (or compression) is any change in the pressure and volume of a gas that may take place without a change of temperature.

When the pressure and the volume of a perfect gas are assumed to change without any change in temperature occurring during the process, the relation between P and V is expressed by Boyle's Law, $PV = \text{a constant}$. Generally, whenever isothermal expansion is assumed, the gases will be considered as approximately obeying Boyle's Law. Thus it is usually said that isothermal expansion is expansion in accordance with Boyle's Law. Since no gas exactly obeys Boyle's Law and many gases act at decided variance with it, the statement that isothermal expansion is expansion in accordance with Boyle's Law is not accurate, but it expresses an assumption which is convenient for purposes of computation. A convenient way of writing the formula is:

$$P_1 V_1 = P_2 V_2$$

Fig. 55 shows the familiar Boyle's Law curves for two temperatures, 100° F. and 400° F.

When a gas under pressure is allowed to expand, it must at least do work against the atmospheric pressure in making more volume available for its occupancy. This work must be done at the expense of the heat energy within itself, therefore, it must be cooled. Then for isothermal expansion of a gas, heat energy must be supplied.

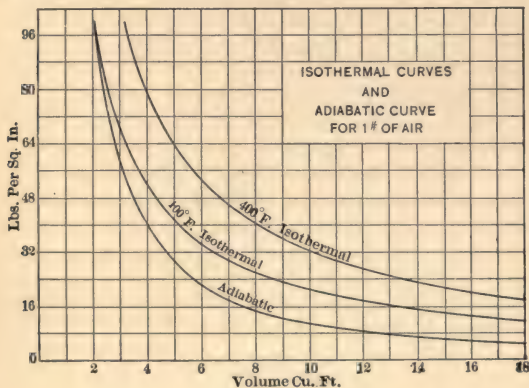


FIG. 55.

Likewise, if isothermal compression takes place it will be necessary to do work upon the gas. This work will appear in the gas as heat energy. Therefore, to have isothermal compression the gas must be uniformly cooled at the same time that it is being compressed.

The energy given up by the gas when expansion takes place is equal to the pressure on the outside of the container times the increase in volume. The work will be in inch-pounds if the pressure is expressed in pounds per square inch and the volume in cubic inches. It will be only necessary

to divide by 12 to change the result to foot-pounds and then by 780 to change to B.T.U. If the expansion is to be isothermal the energy to do the work against the atmospheric or other external pressure must be supplied to the gas from an external source.

Similarly, upon the compression of a gas an amount of work must be done equal to the product of the decrease in volume times the mean pressure of the gas. The energy in B.T.U. will be equal to the volume in cubic inches times the pressure in pounds per square inch divided by 12 and by 780. If the compression is isothermal this energy must be taken from the gas during the process.

70. Adiabatic Expansion. Suppose we have an air-compressor cylinder filled with air, and suppose that the construction of the cylinder is perfect; that is, there are no leaks by the piston, no friction, and the walls of the cylinder, as well as the piston, being made of a non-conducting material. If the piston compresses the air quickly, all of the work expended in moving the piston is done on the gas and *must be in the gas* in the form of heat energy. Such a compression would be called *adiabatic* and would be in accordance with the formula:

$$P(V^y) = \text{a constant},$$

or

$$P_1(V_1^y) = P_2(V_2^y).$$

The exponent y in this formula is the ratio of C_p to C_v or:

$$\frac{C_p}{C_v} = y.$$

Thus y for air is:

$$\frac{.238}{.169} = 1.41.$$

Expansion (or contraction) is said to be adiabatic when it is in accordance with this formula.

Adiabatic expansion would take place in the gas-engine cylinder between the time of the explosion and the opening of the exhaust valve if conditions were ideal. It should also take place in the steam-engine cylinder between the cut-off of the steam and the exhaust of the steam.

Adiabatic expansion assumes:—(1) that a gas gives up *no heat energy* as such, but only as *mechanical energy*, and (2) that it gives up this energy *at a given maximum rate* as called for by the formula.

The first assumption is contrary to practice because in any actual cylinder or other piece of apparatus, conduction to the containing walls and radiation take place. Thus some of the heat energy in the gas is always transferred to adjacent bodies *as heat energy*.

The second assumption is approximately fulfilled in steam engines and explosion motors, where the governor tends to equalize conditions.

There is some confusion in the use of the term *adiabatic*. Whenever a gas expands behind a piston and is made to do useful work the process is commonly called “adiabatic expansion.” However, *true* adiabatic expansion implies that a maximum possible amount of work was done. Whether the maximum amount of work is done will depend in any particular case upon whether the connected machinery reacts and gives a large enough opposing force.

By the definition of a force we know that every action must have its equal reaction. A gas cannot expand and do *useful work* unless there is an opposing force equal to the maximum force which the gas can exert. Where the pressure in the gas is considerably in excess of the pressure opposing it (friction and opposing torque of the connected machinery) the excess pressure in the gas accelerates the fly-wheel, i.e., the excess pressure is balanced by the inertia of the fly-wheel.

In any engine which is provided with a governor, an acceleration beyond normal speed results in a reduction of the gas supply to the cylinder and a consequent reduction of M.E.P., thus equalizing the opposing forces on the piston.

No word is more often used in theoretical discussion of engine performance than the word *adiabatic*. The student must remember that a reference to an *adiabatic*

change merely refers to a change according to the assumed formula. This formula assumes expansion or compression without the taking or giving of energy in the heat form. (See Fig. 55.) *Compression, however, is truly adiabatic*, that is, follows the formula except as the gas loses or gains heat by radiation, conduction and convection.

Problem 6. Suppose a compressor receiving air at 70° F. were to raise the pressure of air in one stage to 15 atmos. abs., what would be the resulting temperature?

The first step is to find the volume of the air at 15 atmos. abs. after adiabatic compression.

$$(1) \quad P_1(V_1^{\gamma}) = P_2(V_2^{\gamma}).$$

12.39 cu.ft. = volume of 1 lb. of air.

$$(2) \quad 1 \times 12.39^{1.41} = 15 V_2^{1.41}.$$

$$(3) \quad V_2^{1.41} = \frac{12.39^{1.41}}{15}.$$

$$(4) \quad \log 12.39 = 1.093.$$

$$(5) \quad \log 12.39^{1.41} = 1.093 \times 1.41 = 1.541.$$

$$(6) \quad \log 15 = 1.176.$$

Subtracting (6) from (5),

$$(7) \quad \log (V_2^{1.41}) = .365.$$

Dividing by 1.41,

$$(8) \quad \log V_2 = .259.$$

$$V_2 = 1.82.$$

The new volume after adiabatic compression would therefore be 1.82 cu.ft. of air.

$$(9) \quad \frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}.$$

$$(10) \quad \frac{1 \times 12.39}{531} = \frac{15 \times 1.82}{T_2}.$$

$$(11) \quad T_2 = \frac{531 \times 15 \times 1.82}{12.39}.$$

$$(12) \quad T_2 = 1170^\circ \text{ F. (Absolute.)}$$

Or $t_2 = 1170 - 461 = 709^\circ \text{ F. final temperature.}$

Problem 7. If an air motor on a compressed-air mine locomotive were to draw in air at 75° F. and 135.3 lbs. pressure; if it were to have 10 per cent clearance and have cut-off take place at such a point in the stroke as to have the air exhausted at .3 lb. pressure at the end of the stroke; find the point of cut-off and temperature of exhaust.

Let V_1 = volume of air in cylinder after admission;

V_2 = volume of cylinder.

Assume adiabatic expansion.

$$(1) \quad P_1(V_1^\gamma) = P_2(V_2^\gamma).$$

$$(2) \quad 150V_1^{1.41} = 15 \times 1.10^{1.41}.$$

$$(3) \quad V_1^{1.41} = \frac{1.10^{1.41}}{10}.$$

$$(4) \quad \log 1.10 = .041.$$

$$(5) \quad \log 1.10^{1.41} = .041 \times 1.41 = .058.$$

$$(6) \quad \log 10 = 1.000.$$

Subtracting (6) from (5),

$$.058 - 1.000 = -.942(9.058 - 10).$$

$$(7) \quad \log V_1^{1.41} = -.942.$$

$$(8) \quad \log V_1 = \frac{-.942}{1.41} = -.668,$$

or

$$\log V_1 = 9.332 - 10.$$

$$(9) \quad V_1 = .215 \text{ volume of air admitted.}$$

Since 10 per cent was the clearance space, the admission valve must have cut off the air supply after the stroke had progressed (21.5–10 per cent) 11.5 per cent of its total motion.

$$(10) \quad \frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}.$$

$$(11) \quad \frac{150 \times .215}{535} = \frac{15 \times 1.1}{T_2}.$$

$$(12) \quad T_2 = 274,$$

or $t_2 = -187^\circ \text{ F. (temperature of exhaust).}$

The foregoing problem shows the result which might be obtained if it were possible to run a motor under conditions giving adiabatic expansion and perfect lubrication at low temperature.

Problem 8. Compressed air for the production of liquid air is often used at an abs. press. of 3000 lbs. If compression were to take place adiabatically from 15 lbs. abs. press. and 60° F. to 3000 lbs. abs. press., what would be the resulting theoretical temperature?

Problem 9. Under the conditions of Prob. 8, it is usual to compress the gas in four stages (or steps) and cool the air between each stage with cooling water. Would it seem wise to you from a study of the temperature produced in each stage to have the abs. press. at the end of stage 1 equal 750 lbs.? stage 2 equal 1500 lbs.? stage 3 equal 2250 lbs.? What temperature would adiabatic compression produce in each stage?

Problem 10. Suppose an ideal air-refrigerating machine used compressed air at 200 lbs. pressure and 60° F. , if it had no clearance, for what part of the stroke should it draw air to exhaust it at 14.7 lbs. pressure? Find the temperature of the exhaust.

Problem 11. Suppose we assume that we are to use an ideal steam engine with no clearance, and we admit superheated steam at 185.3 lbs. pressure and 408° F. If we expand this steam adiabatically to atmospheric pressure, and if the ratio of the specific heats is 1.3, what would be the exhaust steam temperature? The answer will be found to be below 212° F. , the temperature of saturated steam at exhaust. Account for this by explaining what would really happen with steam exhausted as above.

Problem 12. In an NH_3 compressor, the clearance is filled with oil so that conditions may more nearly agree with the ideal adiabatic conditions. If a cylinder is compressing against a back pressure of 28 lbs. gauge to 180 lbs., at what point of the stroke would the exhaust valve open? What would be the theoretical temperature if the NH_3 were at 50°F. before compression?

Problem 13. If the machine mentioned in Prob. 12 handled CO_2 between 350 and 800 lbs., what would be the place in the stroke where the exhaust valve opens and the corresponding temperature, if the temperature before compression is 50°F. ?

71. Quantity of Energy in Gases. Thus far in this text, only the pressure, volume and temperature of a gas have been discussed. If this theory is to be applied practically, however, *the quantity of energy (H)* which is associated with the gas under varying conditions of P , V and T must be considered.

Just how much energy we would have to take out of any particular gas to reduce it to absolute zero we do not know. We have little hope of ever finding out, because we probably will never be able to reach absolute zero and make measurements at that temperature with which to determine quantity relations.

When we speak technically of the quantity of energy of steam, we refer to the total energy which must be added to one pound of water at 32°F. to change it into steam at the given temperature and pressure. This is equal to the sum of the internal energy plus the external energy. The internal energy is in turn made up of latent heat and sensible heat.

Theoretically speaking, a perfect gas should have associated with it a total amount of energy above absolute zero equal to its specific heat C_p times its absolute temperature times its weight. Actually the total heat energy above 32°F. , H_{32} , associated with any permanent gas such as air, hydrogen, oxygen, nitrogen, etc., at atmospheric pressure, will be equal to its temperature, (F) less 32 multiplied by its specific heat (C_p), or

$$(F-32)C_p = H_{32};$$

$$H_{32} = Q_{32} + W;$$

where

$$Q_{32} = C_v(F-32);$$

and

W = external work.

The formulæ for the work done during adiabatic expansion of a perfect gas are expressed as follows:

$$W = \frac{P_1 V_1 - P_2 V_2}{y-1},$$

or

$$W = \frac{R(T_2 - T_1)}{y-1},$$

where V_1 = initial volume in cubic inches;

V_2 = final volume in cubic inches;

W = work done in inch-pounds;

P_1 = initial pressure;

P_2 = final pressure;

T_1 = initial temperature;

T_2 = final temperature;

and

$$y = \frac{C_p}{C_v}.$$

Isothermal expansion is expressed by the following formulæ:

$$W = P_1 V_1 \log_e \frac{V_2}{V_1};$$

or

$$W = RT \log_e \frac{V_2}{V_1};$$

or

$$W = RT \log_e r;$$

where

$$R = C_p - C_v;$$

T = the constant temperature;

and

$$r = \frac{V_2}{V_1}.$$

If P is expressed in pounds per square inch and V in cubic inches, the work is expressed in inch-pounds. Dividing by 12 will change this quantity to foot-pounds, and to change to B.T.U. divide the result in inch-pounds by 12×780 .

The following problem will illustrate the use of this formula:

Problem 14. Find the work done per pound of air in Prob. 7. The formula for the work done in foot-pounds:

$$(1) \quad W = \frac{P_1 V_1 - P_2 V_2}{y - 1}.$$

From Prob. 7 we may obtain the initial volume in cubic feet as follows:

$$(2) \quad \frac{P_0 V_0}{T_0} = \frac{P_1 V_1}{T_1}.$$

$$(3) \quad \frac{14.7 \times 12.39}{493} = \frac{150 \times V_1}{536}.$$

$$V_1 = 1.32 \text{ cu.ft. or } 2,280 \text{ cu.ins.}$$

This air is expanded in the ratio of .215 to 1.1 in the cylinder. Therefore,

$$V_2 = 6.79 \text{ cu.ft. or } 11,700 \text{ cu.ins.}$$

Substituting in (1),

$$(4) \quad W = \frac{150 \times 2,280 - 15 \times 11,700}{1.41 - 1} = 34,300 \text{ ft.-lbs.} \\ = 44 \text{ B.T.U.,}$$

the external work done by the compressed air. This result gives the work which could be delivered by the air motor assuming that it was connected to a suitable load and that it worked adiabatically.

72. Reversible Processes. It is usually stated in connection with a theoretical discussion of engine cycles that all processes are reversible. The new idea that is involved in this statement follows as an axiom, from the statement of the law of conservation of energy and our definition of a perfect gas.

If a pound of a given gas has a pressure P_1 , a volume V_1 and a temperature T_1 , there is a perfectly definite amount of energy associated with it, H_1 . At a new condition, expressed by P_2, V_2, T_2 , the 1 lb. of gas would have a new and definite quantity of energy, H_2 . By whatever plan of varying each factor we make the transition to condition P_2, V_2, T_2 , we will find that in the end the quantity H_2 of energy is in the gas. If we return to the condition P_1, V_1, T_1 , by any method of changing P, V and T which we may choose, we will find that the original quantity H_1 of energy is in the 1 lb. of gas, whenever its condition is expressed by P_1, V_1, T_1 .

In discussing a cycle of operations in a steam or gas engine the condition of the gas is indicated by giving values to P, V and T . Thus the expressions shown below might be used to show that a given mass of gas passed through four distinct conditions:

$$\frac{P_1 V_1}{T_1}, \quad \frac{P_2 V_2}{T_2}, \quad \frac{P_3 V_3}{T_3}, \quad \frac{P_4 V_4}{T_4}, \quad \frac{P_1 V_1}{T_1}, \quad \frac{P_2 V_2}{T_2}, \text{ etc.}$$

There will be a definite quantity of energy in the gas at each condition, namely:

$$H_1, \quad H_2, \quad H_3, \quad H_4, \quad H_1, \quad H_2, \text{ etc.}$$

Now if the order of steps were reversed and taken in the order

$$\frac{P_2 V_2}{T_2}, \quad \frac{P_1 V_1}{T_1}, \quad \frac{P_4 V_4}{T_4}, \quad \frac{P_3 V_3}{T_3}, \quad \frac{P_2 V_2}{T_2}, \quad \frac{P_1 V_1}{T_1}, \text{ etc.,}$$

the energy in each case would be

$$H_2, H_1, H_4, H_3, H_2, H_1, \text{etc.},$$

although the cycle of operations through which the gas was passed was reversed.

The student should remember that these reversible cycles are only approximated in the actual engine. The losses due to friction and conduction effectually prevent an actual reversal of any engine cycle. Every large engine uses a new mass of working medium each cycle which results in leakage losses. In a gas engine the explosion is a non-reversible process.

These reasons for a variation in the performance of any actual engine from theoretical results should always be borne in mind.

In order to obtain the result in Prob. 14 in another way, suppose we start with 1 lb. of air at 135.3 lbs. pressure, 1.116 cu.ft volume, and 75° F. We will cool it at constant volume to .3 lb. pressure. The temperature resulting may be found from the formula,

$$(1) \quad \frac{P_1}{P_2} = \frac{T_1}{T_2}, \quad [(II), \text{page } 83.]$$

or from the formula:

$$(2) \quad P_t = P_0(1 + \alpha t).$$

Using formula (1)

$$\frac{150}{15} = \frac{535}{T_2}.$$

$$T_2 = 53.5^\circ \text{F. (absolute).}$$

Next we will expand it at constant pressure to a volume of 5.728 cu.ft. The temperature will then be 274° F. (absolute). [(I), page 83.]

To cool the gas at constant volume from 535° F. absolute to 53.5° F. absolute would involve the extraction from the pound of

$$(T_1 - T_2)C_v \text{ B.T.U.}$$

$$(535 - 54).169 = 81.3 \text{ B.T.U.}$$

To expand the gas at constant pressure would require the addition of

$$(T_2 - T_1)C_p \text{ B.T.U.}$$

$$(274 - 54) \cdot 238 = 52.3 \text{ B.T.U.}$$

During the expansion at constant pressure external work would be done:

$$(V_2 - V_1) P_2$$

$$\frac{1728(6.76 - 1.32)15}{12 \times 780} = 15.0 \text{ B.T.U.}$$

Therefore of the 52.3 B.T.U. returned to the gas only

$$52.3 - 15.0 = 37.3 \text{ B.T.U.}$$

remained in the gas as heat energy. 81.3 B.T.U. were originally extracted and 37.3 B.T.U. returned, therefore the total energy used externally must have been $81.3 - 37.3 = 44.0$ B.T.U.

This amount agrees with the result obtained above by the formula for work done during adiabatic expansion.

Problem 15. Find the external work done by 1 lb. of air initially at a pressure of 135.3 lbs. and a volume of 1.32 cu.ft. during the expansion to a volume of 6.76 cu.ft. at a constant temperature of 75° F. (Remember that this is expansion according to Boyle's Law.)

Problem 16. With cooling water in a condenser how much energy may be taken out per pound of air compressed in a cylinder working adiabatically, without clearance, between atmospheric pressure and 225 lbs. gauge? Assume initial temperature of air, and also of the circulating water leaving the condenser through which the compressed air is led, to be 60° F.

Problem 17. If this air in Prob. 16 were then expanded adiabatically to atmospheric pressure, what would be its temperature? How much energy could it take up in warming to 60° F. after adiabatic expansion?

Problem 18. If the expansion in Prob. 17 had been into the atmosphere (or free as we say) what would have been the final temperature and the amount of energy absorbed per pound in warming to 60° F.?

Problem 19. 80° F. is the temperature of the air and gas charge drawn into the cylinder of a gas engine having a clearance of 15 per cent. The cylinder is filled at a pressure of 14 lbs. absolute. What will be the temperature and pressure when the engine is on dead center and all the gas charge has been

compressed into the clearance? How much energy has been given to the gas during the compression?

Problem 20. If a gas engine has 15 per cent clearance and after the explosion of the charge the gases have a temperature of 2200°F . and a pressure of 180 lbs., find the temperature and pressure of exhaust and the work done during the working stroke. Assume adiabatic expansion $\gamma = 1.40$.

73. Entropy. There is one very important case in which a number, of which the quantity of heat in a gas is a factor, is numerically used in a formula involving pressure and volume.

In adiabatic expansion we have $PV^{\gamma} = \text{a constant}$.

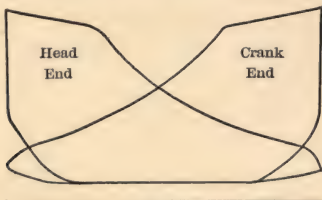


FIG. 56.

A numerical factor in this constant is equal to $\left(\sum \frac{H}{T}\right)$.

This $\sum \frac{H}{T}$ is called the *entropy* of the substance.

The numerical quantity which we call entropy is used as a label to tell us something about how the energy is associated with a substance. The student will best learn what this word means by using the quantity in the solution of problems.

A very good illustration of the use of the quantity in computation is offered by practical problems upon steam and steam engines.

In speaking of the entropy of steam, the $\sum \frac{H}{T}$ is computed for the quantity of heat added in making the steam

from water at 32° F. Thus the entropy of steam is a function of the total heat of steam as given in the steam tables. Thus, if the steam was at 32° F. the only energy it would contain above 32° F. would be all due to its latent heat. Since this is all added at 32° F., or 492° absolute F., the entropy would be the latent heat divided by 492, or

$$\frac{1072}{492} = 2.180.$$

This quantity (2.180) is called the gain in entropy during vaporization.

The entropy of steam at 33° F. is made up of two parts, the entropy of the liquid and the entropy of vaporization.

If the specific heat of water were uniformly 1, the entropy at 33° F. would be

$$\frac{1}{492.5} + \frac{1071}{493} = 2.177.$$

The entropy of the liquid at 212° F. would be the sum of the series:

$$\frac{1}{492.5} + \frac{1}{493.5} + \frac{1}{494.5} + \text{etc.}, \text{ to } \frac{1}{671.5} = .3125.$$

The entropy of dry saturated steam at 212° F. would be the sum of the entropy of the liquid and the entropy of vaporization, or

$$.3125 + \frac{970}{672} = .3125 + 1.4441 = 1.7566.$$

On the other hand, if the steam contained some fog and had a quality of only .99, the entropy of the steam would be

$$.3125 + .99 (1.4441) = 1.7421.$$

Thus we may say that the *entropy* of a substance is a numerical factor which, when taken in conjunction with

the pressure and volume of a substance, tells us the quantity of energy in it.

If we have steam under 14.7 lbs. pressure and its entropy is 1.800 we know that it contains more energy than dry saturated steam, i.e., it is superheated enough to give it an additional entropy of .04 above that of dry saturated steam. If the specific heat is assumed to be constant and .5, then .04 equals the sum of the series:

$$\frac{.5}{672.5} + \frac{.5}{673.5} + \frac{.5}{674.5} + \text{etc. to } \frac{.5}{671.5+x},$$

where x is the number of degrees of superheat.

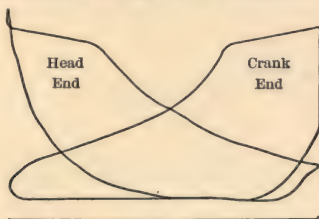


FIG. 57.

Table X shows the entropy, volume per pound (specific volume) quality, pressure, and temperature of saturated steam at the pressure given on the same line. While this table is usually called a Temperature-Entropy Table, it would be more logical to call it a Pressure-Entropy table, for the horizontal lines simply indicate the pressure of the steam and the vertical columns the entropy, etc.

Wherever we have saturated steam, the temperature for all qualities will be as given in the first column of the table. If the steam quality shows superheating, the quality plus the temperature in the first column will be the true temperature of the steam.

The use of this table is illustrated by the following problems.

Problem 21. A steam engine is supplied with steam at 205.4 lbs. and superheated 167° F. If each cylinder had no clearance, worked adiabatically, and exhausted the steam against a back pressure of .7 lb., what would be the energy left in the steam and the theoretical heat efficiency of the engine?

By consulting the table, the entropy of steam at 220.1 lbs. absolute and 167° superheat is found to be 1.64 and the total heat content 1293.6 B.T.U. In the 1.64 column opposite .7 lb. pressure we find the quality to be .8066 and the total heat content 897.9. The energy left in the cylinder would be

$$1293.6 - 897.9 = 395.7 \text{ B.T.U.},$$

and the efficiency (Rankine cycle) is

$$\frac{395.7}{1293.5} = 33 \text{ per cent.}$$

It will be noticed that the exhaust of this engine would contain nearly 2 per cent water in spite of a rather large superheat.

REVIEW PROBLEMS, CHAPTER VIII

22. Compute the specific heat of a mixture of 4 lbs. of air and .8 lb. of CO .

23. If this mixture burned resulting in 1.3 lbs. CO_2 and 3.5 lbs. of nitrogen, compute the specific heat of the products of combustion.

24. If the weight of 1 cu.ft. of hydrogen is .005621 lb., compute the ratio between C_v and C_p at 0°C . Assume that $C_p = 3.400$. How much is C_v for hydrogen according to your computation?

25. A value often given for water is $y = 1.33$. Compute and record in your table the value of C_p .

26. Given for bromine $y = 1.293$. Compute and record in your table the value of C_p .

27. Given for chloroform $y = 1.102$. Compute and record in your table the value of C_p .

28. For sulphuric ether C_p at $40^\circ = .42$, and $y = 1.03$. Compute C_v and record its value in the table.

29. Compute from Prob. 26 and the tables the density of bromine at 147°C .

30. From Prob. 27 and the tables compute the density of chloroform at 107°C .

31. From Prob. 28 and the tables compute the density of ether at 137°C .

32. Compute as in Prob. 5, p. 202, the value of R for bromine, chloroform, ether, and water.

33. An ammonia compressor draws gas at 42°F . and 28-lb. gauge pressure. It discharges the gas at 165 lbs. gauge and 102°F . Assume that 1 cu.ft. of ammonia at 32°F . weighs .0476 lb. and apply the laws of a perfect gas to obtain weights per unit volume at other temperatures. Compute actual work done upon it.

34. How much work would have been done in Prob. 33 if the compression had been isothermal?

35. If in Prob. 33 adiabatic compression had been assumed, what must have been the final temperature?

36. If adiabatic compression took place in Prob. 33, how much work must have been done?

37. In Prob. 36 at what point in the stroke did the exhaust valve open?

38. A triple-expansion engine receives steam under 196 lbs. absolute pressure and superheated 149° . It exhausts into a low-pressure turbine which in turn exhausts into a condenser against a back pressure of .70 lb. If the expansion had been adiabatic, compute the volume of 12 lbs. working medium as exhausted.

39. Compute the pounds of steam per I.H.P. per hour in Prob. 38.

40. How many B.T.U. must have been left in the cylinder per pound of steam in Prob. 38?

41. In Prob. 13 adiabatic compression is assumed; find the temperature of the exhaust.

42. How much energy must be taken out by cooling water if 1 lb. of air at 15 lbs. pressure is taken in at 70° F. and is to be delivered at 70° F. and 90 lbs. gauge pressure?

43. If the compression in Prob. 42 had been isothermal, how much heat must have been taken out during the stroke? Compare this result with the answer in Prob. 42.

44. A gas engine has a clearance of 20 per cent. It draws a charge of gas at a mean temperature of 75° F. Assuming that this charge has the same physical properties as air, what was its temperature when it had been adiabatically compressed into the clearance?

45. In Prob. 44 how much work was done by the fly-wheel during compression per pound of gas compressed?

46. In Prob. 38 what was the efficiency, assuming the conditions in the Rankine cycle?

47. Using the formula for an all-gas cycle, compute the efficiency and compare your result with that obtained in Prob. 46.

48. An engine works on the Rankine cycle and uses steam having an entropy of 1.64 under 200 lbs. pressure. What was the temperature of the steam?

49. In Prob. 48 what was the efficiency if the steam was exhausted into a condenser against a back pressure of .5 lb. abs.?

50. In Prob. 49 compute the steam consumption in pounds per hour per I.H.P.

51. In Prob. 49 what would be the efficiency assuming an ideal all-gas cycle?

52. Assume the conditions of the Rankine cycle and that an engine receives dry saturated steam at a temperature of 340° F. The steam is exhausted into the atmosphere. Compute the B.T.U. left in the cylinder.

53. Compute the efficiency in Prob. 52.

54. Compute the energy left in cylinder in Prob. 52 if a condenser in which an absolute temperature of 1.1 lbs. was maintained had been used.

55. Compute the efficiency in Prob. 54.

56. If steam were used adiabatically in a compound engine and if a steam trap were introduced between the two cylinders, how much water *could* be drawn off at the trap (under perfect conditions of separation) and what would be the weight of water in the exhaust? Assume that the steam entered the second cylinder dry and that both cylinders worked upon the Rankine cycle.

Pressure in steam main = 153 lbs. abs.

Degree superheat = 48.7° F.

Pressure at receiver, between cylinders = 80.0 lbs. abs.

Pressure at condenser, between cylinders = 1.47 lbs. abs.

57. In Prob. 56 what would have been the quantity of heat left in the cylinders?

58. In Prob. 56 what would have been the efficiency?

59. If in Prob. 56 no water had been extracted between the two cylinders, what would have been the efficiency?

60. What would have been the efficiency assuming an all-gas cycle in Prob. 52?

61. What is the entropy of 1 lb. of steam containing 1280 B.T.U. at 208 lbs. absolute pressure?

62. The following data applies to oxygen cylinders used with pulmotors:

Weight of cylinders filled with oxygen at atmospheric pressure = 10 lbs. 4 ozs. 11 drams;

Weight of cylinder after it has been filled to contain 150 atmospheres of oxygen gas = 11 lbs. 3 ozs. 3 drams.

If the room temperature is 20° C., compute

(a) How many liters of gas can the cylinder deliver?

(b) How many cu.ft.?

(c) How many gallons?

63. After the pressure of the gas in the above cylinder has been reduced to 80, compute

(a) How many liters of gas the cylinder has delivered?

(b) How many cu.ft.?

(c) How many gallons?

SUMMARY, CHAPTER VIII

There are two specific heats of a gas. The numerical value of **THE SPECIFIC HEAT AT CONSTANT VOLUME** is equal to the quantity of heat energy necessary to raise a unit mass of the gas one degree.

The numerical value of **THE SPECIFIC HEAT AT CONSTANT PRESSURE** is equal to the energy required for expansion at constant volume plus the external work done in increasing the volume.

ISOTHERMAL EXPANSION is expansion at constant temperature.

ADIABATIC EXPANSION is expansion under a set of assumed conditions which are never obtained in practice. These are that no energy be received nor given up by the gas except energy in the mechanical form. True adiabatic expansion implies a maximum rate of transfer of energy and obeys the formula

$$P_1 V_1^{\gamma} = P_2 V_2^{\gamma} = \text{a constant.}$$

When the above formula holds, the work done during adiabatic expansion may be computed from

$$W = \frac{P_1 V_1 - P_2 V_2}{\gamma - 1}.$$

ENTROPY is a numerical factor in the constant in the formula for adiabatic expansion, and is obtained by computing $\text{SUM } \frac{H}{T}$.

CHAPTER IX

CONVECTION, CONDUCTION, RADIATION, AND THE INSULATION OF BODIES

74. Convection of Heat Energy. The illustrations of convection currents in fluids are so numerous that students in general are familiar with the term.

Convection, as the etymology of the word suggests, refers to the carrying about of heat by circulating masses.

Whenever the lower portion of a fluid receives heat energy from an external source, a small portion nearest the source becomes warmer, and expanding, grows less dense than the remainder of the fluid.

Therefore the downward gravity pull upon the warmer, less dense fluid becomes less, bulk for bulk, than that upon the surrounding colder fluid, and just as the heavy pan of a balance is pulled down thus lifting the lighter pan, so the colder portion of fluid is drawn down and the light portion forced up. By this means currents are set up which tend to stir the mass until it becomes of uniform temperature. If heating from the top takes place, no such circulation results, for the heavy portion is at the bottom, where it will stay unless moved by an external force.

If we notice the air currents in a steam-heated room, we find that cold air at the bottom of a radiator comes in contact with the hot surface of the metal and is heated by it. The energy gained by the gas causes it to expand and its density to decrease below that of the cooler air in the room. The less dense hot gas floats up to the top just as a light liquid, such as kerosene oil, floats to the top of a heavier liquid, such as water. As the convection currents

rise, the heated gas may come in contact with the cooler walls and give up part of the energy gained from the steam pipes. As soon as it is cooled by giving up its heat, this air becomes more dense than the air which is being heated by the steam pipes. If the room is closed, this dense air will drop down in the parts of the room remote from the radiator, crowding upward the warm air beside the radiator. After mixing with other air it may again go over the steam pipes and repeat the trip about the room.

From this illustration it will be seen that energy is not passed along by convection currents except by the simultaneous movement of masses of the fluid. Convection currents may occur in liquids and gases. A solid cannot have convection currents set up among its molecules and accordingly we cannot heat a solid internally by convection.

All ventilating and heating systems for houses, etc., take advantage of this principle to distribute artificial heat about in each room. The hot-water system, and the hot-air furnace system also depend upon convection to convey the energy from the furnace to the several rooms to be heated. Our winds, in most cases, are nothing more than convection currents on a large scale.

In the steam boiler, the convection currents play a very important part. In the boiler shown in Fig. 40, the heating of the water in the water tubes not only expands the water and diminishes the density of the water, but also causes some steam to form. The density of the mixture is very much less than that of the water at any temperature. The water in the rear water leg *M*, being more dense, settles, moving the mixture of water and steam up in the front head *B*, and from there back into the boiler. The proper action of the boiler is dependent upon so constructing the tubing and headers that the convection currents will produce a rapid, continuous circulation.

This force, which moves the mass of fluid upward when convection currents are established, is due to the difference

between the weight of the column of hot fluid and that of a cold column of equal length and cross-section. Thus the force which is tending to move the air up the chimney in Fig. 62 would be computed as follows:

The height of the chimney is 100 feet.

The temperature of the gases in the chimney is 600° F.

The temperature of the outside air is 75° F.

The weight per cubic foot at 75° is

$$\frac{T_1}{T_2} = \frac{D_2}{D_1} \quad \text{or} \quad \frac{461 \times .0864}{536} = .0742 \text{ lb.},$$

and similarly the weight at 600° F. = .0375.

The difference in weight per cubic foot = .0367. Therefore this difference times 100 gives the moving force per square foot of cross-section at the base, or $.0367 \times 100 = 3.67$. The moving force in pounds per square inch would equal

$$\frac{3.67}{144} = .025.$$

In practice a draft gauge is used to measure this force. This is simply an open-arm manometer such as the student has used to measure the pressure of the gas in the laboratory. The difference in pressure on the two sides of the U tube causes the water to stand one inch higher on the side communicating with the chimney for every .036 lb. of pressure. Therefore the difference in pressure between the atmosphere and the inside of the chimney will be measured by the number of inches on the draft gauge times .036 lb.

The Draft of a Chimney. The velocity of the gases issuing from the chimney depends upon so many factors that most engineers rely upon tables based upon experience to supply the data from which to design new stacks.

The preceding problem explains the draft of a chimney.

Theoretically the velocity of the gases coming out of the chimney would be as expressed by the following formula:

$$V = \sqrt{2gh},$$

where V = velocity;

h = the difference between the height of the chimney and the height to which a column of gas of the same length and cross-section area as the chimney would extend if heated from the temperature of the outside air to the temperature of the chimney;

g = the acceleration due to gravity.

The actual formulæ in use are based more upon experience than theory. (See any handbook.)

75. Conduction of Heat Energy. Conduction is very different from convection. For instance, if heat energy is supplied to one end of a metal rod the energy is passed on from layer to layer until it reaches the other end. If you stick a metal rod of any convenient length, such as 1 ft., in the fire and hold the other end in the bare hand it very quickly becomes uncomfortably warm.

When heat energy is transferred from one part of a body to another, without motion of integral parts of the body, intervening parts being also heated, the process is called *conduction*.

Instead of using one rod let the student select two rods, one of copper and the other of iron, each of like dimensions, such as $\frac{1}{4}$ in. in diameter and 24 ins. in length, and, holding one in each hand, let him place an end of each rod in the forge fire. The heat from the fire will be conducted through the metal to the hand and the copper rod will be too hot to hold while the iron rod is still cold. The rate of transfer differs for each solid material, but, in general, it is true that good electrical conductors are also good heat conductors.

The process may best be understood by thinking of the molecular structure of the body and the Kinetic Theory.

We may think of each circular section of the copper rod as consisting of a sheet, 1 molecule of copper in thickness. When the end is thrust into the fire the molecules in the end section are quickly heated and have their kinetic energy (or $\frac{1}{2}MV^2$) greatly increased. The increase in the energy of the molecules in this section results in their impinging against the molecules of the next adjacent section with greater velocity and much of the newly added energy of the molecule of the first section is transferred to the second during the impact. Thus the mean velocity of the molecules is increased from layer to layer outward from the source of heat at a rate dependent upon the nature of the material.

To gain a better understanding of the conditions controlling the rate of transfer of heat by conduction let us assume a set of conditions. Suppose a conducting sheet of uniform thickness separates a region of high temperature t_1 from a region of lower temperature t_2 . A quantity of heat energy Q will be conducted through, which will depend upon the following factors:

1. The quantity passing through the conductor will be in direct proportion to the area A of the conductor. In this case just as in a water pipe the greater the area of the section through which the flow takes place, the larger the volume which may flow. It follows that

$$Q \propto A.$$

2. The rate of flow through the conductor will depend upon the difference in temperature between the two sides. This difference may be compared to the difference in pressure which forces a stream of water through a length of pipe. No flow can take place through the pipe without a difference in pressure.

It does not follow, however, that the amount of flow is in direct proportion to the difference in temperature, although this is usually assumed in the case of a heat conductor.

It follows that $Q \propto t_1 - t_2$.

3. The amount of flow will decrease as the length of the path increases. It is usually assumed that the quantity of energy transferred is inversely as the thickness of the conductor. Here again the conditions are analogous to those in a water pipe. The greater the length the less the flow under a given set of conditions of size of pipe and pressure.

It follows that $Q \propto \frac{1}{\text{thickness}}$.

4. The amount of flow depends upon a constant factor, K , which expresses the effect of the kind of material used and the ability of that particular material to conduct heat.

5. The total amount of flow depends upon the time, which is usually expressed in seconds when the metric system of units (incorrectly but commonly called in this case C.G.S. units) is used, and in hours, minutes, or seconds, when the English system is used.

It follows that $Q \propto \text{time}$.

These controlling factors when combined give us the result

$$Q \propto \frac{K \times A \times (t_1 - t_2) \times \text{time}}{\text{Thickness}}.$$

Or if K be given a proper value to correspond with the units of size, length, temperature, and time which are to be substituted,

$$Q = \frac{K \times A \times (t_1 - t_2) \times \text{time}}{\text{Thickness}}.$$

From this equation a value for K may be found.

There are two common ways of expressing K , the "Conductance," or the coefficient of conductance as it is called in most reference and text-books, as follows:

Coefficient of conductance (metric units) =

$$= \frac{\text{Calories per sec.} \times \text{thickness in cms.}}{\text{Area of surface in sq.cms.} \times \text{temp. difference in deg. C.}}$$

Coefficient of conductance (British units) =

$$= \frac{\text{B.T.U. per hr.} \times \text{thickness in inches}}{\text{Area of surface in sq.ft.} \times \text{difference in temp. in deg. F.}}$$

Or, in other words, the conductance has been given usually either as calories per second through a centimeter cube or as B.T.U. per hour through a square foot section 1 in. thick.

There is a close analogy between the conduction of heat energy through the material and the conduction of electrical energy through a material. Thus a third way of measuring conductance has arisen. If the difference in pressure of the heat energy is the difference in temperature (c) at the two ends, the current of heat energy may be measured in watts, and the resistance to flow of heat in "thermal ohms" and the conductance in "thermal mhos." *

Using these terms, we might say that for a square centimeter cross-section and a centimeter length,

$$\frac{t_1 - t_2}{\text{watts}} = \text{thermal ohms,}$$

where t_1 and t_2 are the temperatures centigrade,
or

$$t_1 - t_2 = \text{watts} \times \text{thermal ohms,}$$

$$t_{\text{dif}}^0 = \text{watts} \times \text{thermal ohms.}$$

* These units have been suggested by Carl Hering, Past President of the American Institute of Electrical Engineers, in the following articles:

Flow of Heat through Bodies; Metallurg. & Chem. Eng. Dec., 1911, p. 652.

Thermal Resistance and Conductivity; Metallurg. & Chem. Eng. Jan., 1911, p. 13.

Simplification of Electrical Calculations; Proc. A.I.E.E., June, 1912.

In these articles it is pointed out that the true C.G.S. unit of conductance would be an erg per sec. through a cm. cube.

Since calories per second and B.T.U. per hr. are both power units, when the source of energy is electrical, it is more convenient as well as more logical to use watts as a factor.

The thermal conductance, or, as it is frequently called, the coefficient of conductivity, is the reciprocal of the thermal ohm and is called the thermal mho. It is the product of the difference in temperature between any two sections 1 cm. apart and the watts passing through a centimeter cube of material between these sections.

$$\text{Temp. difference} = \text{thermal ohms} \times \text{watts.}$$

A serious limit is placed upon the usefulness of this formula by the fact that the resistance is not constant for any substance. The thermal resistance of some metals increases with the temperature. Other metals decrease in resistance with increase in temperature. Still other metals act irregularly. As an example of this, iron, according to one writer, has a resistance, in thermal ohms of approximately 1.2 at 0° C., 1.1 at 100° C., and 1.9 at 275° C. There is also a great deviation in values given by various investigators. This requires that a determination of the value of the thermal ohm be made for each practical computation.

Following the electrical analogy, the thermal ohms resistance, R , for any body of other than unit dimensions would be

$$R = \frac{rl}{a},$$

where r is the resistance of the substance under unit conditions, l the length of the path through which the heat flows, and a the area of the path.

There are two large fields for the use of the conductance, K , in practical computations. First, the insulation of refrigerating plants, piping and boilers. Second, the construction and insulation of furnaces and high-temperature apparatus.

The constant is determined in the first type of problem, using the materials under as nearly the same conditions

during the test as pertain in practice. In that case the coefficient is not necessarily a true value for the particular materials in use, but will express the effect of other limiting conditions. Computations of this character are usually in the British system.

In the case of extremely high temperatures the conductance, K , may be computed from practical tests of the material under working conditions just as in the case of low-temperature insulation. In this event the true conductance is not usually found, but a coefficient which is affected by the peculiar conditions under which the material is to be used and the test is taken. Computations with a factor, K , obtained thus will be fairly accurate. For electric furnaces it is most convenient to find K in thermal mhos.

The practical value of a true coefficient, K , is somewhat limited by the fact that in most cases the heat must pass from a fluid on one side of the substance to a fluid on the other and the rate of flow through the contact surfaces apparently does not obey the law which applies to solids. However, problems of the character shown below are frequently worked out, assuming that the flow takes place in accordance with the general law.

K has the same general significance in either system of units, but it has a different numerical value in each system. This difference in value is due to the difference in size of the units of area, thickness, temperature, and time used in each case.

See Table XIV for approximate values of K .

An average piece of wrought iron may be said to have a resistance in thermal ohms of 1.2 at 0°C . If its conductance is wanted in thermal mhos it will be $\frac{1}{1.2}$ or .83.

If the conductance (or the coefficient of conductivity) in metric units is desired it may be computed as follows:

Assume a difference of temperature between the two opposite faces of a centimeter cube to be 1°C ., then from the above statement it follows that .83 watt will flow through this cube per second. Now,

there are 4.19 watts in one calorie. Expressed in calories the flow through this cube will be $\frac{.83}{4.19} = .20$.

If the conductance is to be expressed in B.T.U. per square foot per hour for a 1° F. difference in temperature and a 1-in. thickness there are five factors which must be considered:

First. 1° C. = $\frac{5}{9}^{\circ}$ F. Therefore, the flow would be less through the section and it will be necessary to multiply the .20 calories by $\frac{5}{9}$.

Second. 1 sq.ft. = 929 sq.cms. Therefore, there will be 929 times greater flow through a square foot section than through a square centimeter section. It is necessary to multiply by 929.

Third. 1 in. = 2.54 cms. Since the quantity must flow through 2.54 times the thickness there will be only $\frac{1}{2.54}$ of the flow.

Fourth. 1 hr. = 3600 secs. There will be 3600 times the quantity flow in an hour.

Fifth. 252 calories = 1 B.T.U. To change the quantity from calories to B.T.U. it is necessary to divide by 252.

Thus,

$$\frac{.20 \times 5 \times 929 \times 3600}{9 \times 2.54 \times 252} = 570 \text{ B.T.U.}$$

Problem 1. Lead is stated by one author to have a coefficient of conductivity of .084 in metric units. What is the conductivity in thermal mhos and the resistance in thermal ohms?

Since one calorie is equivalent to 4.18617 watts, and both units state the energy passing through a centimeter cube, all that is necessary is to multiply by 4.186 to convert calories per second into watts.

$$.084 \times 4.19 = .344 \text{ thermal mho.}$$

$$1 \div .344 = 2.08 \text{ thermal ohms.}$$

Problem 2. A second author states that lead has a coefficient of 287 B.T.U. per square foot per hour per degree F. Convert to thermal mhos and thermal ohms.

To change this to watts per centimeter cube per degree centigrade difference in temperature, or in other words to thermal mho,

$$\frac{9}{5} \times \frac{287 \times 252 \times 4.19}{144 \times 60 \times 60 \times 6.45} = .163 \text{ thermal mho.}$$

The resistance = 6.13 thermal ohms.

Problem 3. Suppose a sheet of $\frac{1}{2}$ in. copper (see page 307) were to have one side in contact with water under 120 lbs. pressure and the other in contact with gases at 1500° F., what would be the resulting evaporation per hour per square foot of surface?

(Assume feed water to be at the boiler temperature.)

$$(1500 - 350) \times \frac{2600}{.5 \times 870} = 6900 \text{ lbs.}$$

This problem shows conclusively that boiler tubing never reaches a temperature of the same order as that of the gases in contact with it.

Problem 4. If sawdust has a coefficient in British units of .4, what is the weight of the ice melted per day in an $80 \times 40 \times 40$ ice-house through a thickness of 8 ins. if the outside temperature is 80° F.? Disregard melting at top and bottom.

$$\frac{[2(40 \times 80) + 2(40 \times 40)] \times .4 \times (80 - 32)}{144 \times 2000 \times 8} = 2.56 \text{ tons.}$$

Problem 5. What would the results in Prob. 2 be in watts per inch cube and in resistance per inch cube?

Problem 6. Kent's Handbook gives silver as having a conductivity of 1000 in B.T.U. per degree F. per square foot area per inch of thickness (British system). What would this conductivity be in the so-called "C.G.S. units"?

Problem 7. What would be the evaporation of water per hour per square foot through a boiler plate of $\frac{1}{4}$ in. iron, if the temperature difference were 100° F. and if the coefficient of conductivity in British units were 160?

Problem 8. If a boiler has 12 sq.ft. of mean boiler surface for each H.P. of boiler rating, and if the boiler tubing is .12 in. thick, what difference in temperature exists between the two surfaces of the tubing?

Problem 9. What would be the temperature difference in Prob. 9 if the tubing had been copper?

Problem 10. What would have been the difference in temperature in Prob. 9 if the tubing had been brass (conductance in C.G.S. units = .265) and if the boiler were working at a 50 per cent overload?

Problem 11. Compute the constants to convert thermal conductance from "C.G.S." units to British units and record in your book.

76. Insulation. There are two ways of considering the flow of heat through bodies by conduction. When one speaks of the ease of flow he measures the effect in terms of the unit of conductance, the thermal mho (or the coefficient of conductivity). When one thinks of the reverse effect, the resistance of the material to flow, he will measure the property of the material in "thermal ohms," which are obtained by taking the reciprocal of the thermal mhos. The choice of term depends upon the use to which we put the material. Copper tubing is introduced into a boiler so that heat energy may be conducted through the walls of the tube to the water within as quickly as possible. In English locomotives, the firebox is often made of copper because it is the best cheap metallic conductor of heat and accordingly permits a greater amount of steam to be made per square foot of surface exposed to gases than would any other material. We then say that copper is a good *conductor*, and in such instances would measure the flow of heat in terms of thermal mhos.

We cover the outside of boilers with lagging in order to keep heat from being conducted away. Here we want a poor conductor of heat and we say we have used an "insulator." The property by virtue of which it resists the flow of heat would be measured in thermal ohms.

These terms are similarly used in electricity.

Sawdust, charcoal, asbestos, and various other porous materials are in very common use to prevent the conduction of heat away from warm bodies or into refrigerating piping, cold storage rooms, ice houses, and the like. These are used because they all fill the first of the following set of requirements for a good insulator. The common materials in use for this purpose, besides being cheap, should have low heat conductivity, should be non-inflammable, mechanically strong enough to stand handling, vibration, and heat fluctuations, chemically constituted so that they do not corrode or decompose when subjected to heat and moisture.

A light, porous material that entangles a large amount of air within itself is specially good, provided that it does not have single spaces large enough to allow convection currents. Enclosed air is a very bad conductor. Asbestos forms a part of most laggings, and besides being used alone is frequently used to bind together other insulating compounds of magnesium, carbonates, various silicates, etc.

While these materials make the conduction of heat slow, even better results are obtained if the outside is painted to give it a glazed surface.

Conduction from a solid surface to an adjacent layer of fluid is greater from a matt surface than from a smooth surface.

Problem 13. A refrigerator is made up of layers of material in the following order:

$\frac{7}{8}$ in. matched pine boards;

Damp-proof paper;

$\frac{7}{8}$ in. matched boards;

2-in. joists providing a space which is filled with sawdust;

$\frac{7}{8}$ -in. matched boards;

Waterproof paper;

$\frac{7}{8}$ -in. matched boards;

2-in. joists to make an air-space;

$\frac{7}{8}$ -in. matched boarding;

Damp-proof paper;

and $\frac{7}{8}$ -in. matched boarding.

What would be the conductance of the combination? (Neglect the paper.) The resistance of the whole wall is the sum of the resistances of each layer of material. There are six thicknesses of $\frac{7}{8}$ -in. boards and their combined thermal resistances are as follows:

$$\frac{7}{8} \text{ in.} \times 6 \times 2700 = 14,180 \text{ thermal ohms.}$$

The thermal resistance R of 2 ins. of sawdust is

$$2 \times 1560 = 3120 \text{ thermal ohms.}$$

The thermal resistance of 2 ins. of air is

$$2 \times 2000 = 4000 \text{ thermal ohms.}$$

Adding these quantities, we have 21,300 thermal ohms

as the total resistance, and the conductance is .000047 thermal mho.

Problem 14. A refrigerator box has an area of 1000 sq.ft. Its walls are 8 ins. thick and have a conductance of 2.2 B.T.U. The temperature is to be kept at 30° F. when the external temperature averages 80° F. for 24 hours. What would be the B.T.U. per hour conducted away?

Problem 15. What loss per hour will result from the storage of liquid air in a glass vessel $\frac{1}{16}$ in. thick of 1 sq.ft. area of surface, if the outside were at 20° C. and the inside at -180° C.? Explain why this result does not really agree with practice.

Problem 16. A refrigerator has a single glass window of 4 sq.ft. area. If the inside is at 36° F. and the outside at 70° F., what ice loss is produced thereby per day?

Problem 17. What would be the conductance in British units in Prob. 13?

Problem 18. A steam main carrying steam at 200 lbs. pressure in a room at 75° F. has a total area of lagging of 168 sq.ft. If the lagging is 2 ins. of magnesia having a resistance of 1400 thermal ohms per centimeter cube per degree centigrade, what is the B.T.U. loss per hour for the entire length?

Problem 19. What weight of ice in melting would absorb the added energy due to the heating through brine pipes lagged with a total area of 200 sq.ft. of 2 ins. thick asbestos with a conductivity in C.G.S. units of .00030? Difference in temperature between the brine and air 85° F.

77. Radiation. It has already been stated on pages 7 and 8 that radiation is due to a wave motion and that this wave motion is always accompanied with a giving of energy by the body emanating the rays. When the body is very hot the wave motion affects our eye and we call it light. Even though we do not see the rays it is true that all bodies are giving off energy in wave form. We have all experienced the blistering effect of these waves which come from regions of temperature below 700° C as we have stood about bonfires. They pass through a vacuum without heating it, i.e., without loss of energy, and there are many substances such as hard rubber and glass which allow certain of these rays to pass through without greatly heating the medium. The energy radiated from the sun in clear,

dry weather is transmitted through the atmospheric air to the earth with very little loss. These radiations come through the region of air 100 miles in depth with a loss which has been estimated as less than 20 per cent under the most favorable conditions.

The *wave length* is the distance from the crest of one wave to the crest of the next wave. This length is the same as the distance between the similar parts of any two adjacent waves.

Radiations are often discussed under three different topics: Light, ultra-violet light, and heat radiations. These rays are all alike in character and differ from one another only in wave length and amplitude. If one were to heat a piece of iron to 400° F., the wave lengths would be not longer than 140 millionths of a centimeter. One could not see any light rays coming from the iron, but he could feel the heat rays without touching it. Heat the iron further to about 975° F. and there would be a few rays as short as 80 millionths. The eye will begin to be affected by these radiations and will record a faint red color. Other colors are seen about as follows:

Dull red	1300° F. = (a larger quantity of 80 millionth wave lengths)
Cherry from 1500° to 1800° F.	= (65 millionths length in quantity)
Orange from 2000° to 2200° F.	= (55 millionths length in quantity)
White from 2350° up	= (50 millionths length in quantity)
Dazzling from 2700° up	= (45 millionths length in quantity)

At just what temperature ultra-violet rays (of less than 40 millionths) begin to be produced by a hot body is not so definitely shown, but they are present in considerable quantity in the radiation from a body at 2500° F. While

the eye sees by means of the rays between 80 and 40, the ultra-violet rays, of length shorter than 40, affect the sensitive material on the photographic film and it is only by means of the camera, spectroscope, radiometer, bolometer, and such delicate instruments that we may study such rays. The greater part of the energy radiated by all sources of light mentioned in Table XII is in the form of the long wave length heat radiations. The ultra-violet rays take away only a very small per cent of the energy of even such very hot bodies as the arc lamp. The glass globe of an arc lamp screens them effectually. Strong ultra-violet rays produce very bad flesh burns which are difficult to heal.

There is a mercury vapor arc lamp which has found occasional use in Europe which operates at an extremely high temperature and must therefore be enclosed by a quartz tube. Since quartz transmits ultra-violet rays and since this lamp emits an unusual quantity of these rays, it has been found necessary always to inclose the arc with a second globe of glass to avoid burns.

78. Radiation Laws. "NEWTON'S LAW OF COOLING" states that the rate of loss of energy from a body is in direct proportion to the difference between its temperature and that of its surroundings.

To illustrate this, suppose that the crucible used in obtaining the data for Fig. 23 had been allowed to cool to the room temperature. If Newton's law holds true, the rate of loss would have been twice as great when the crucible was 100° hotter than the room than when it was 50° hotter. When the temperature reached 50° it would take twice as long to cool 1° as it took at 100° . Similarly, at 25° the rate of loss would be only one-fourth of that at 100° . Accordingly the time would be four times as long at 25° as at 100° .

When there is a considerable difference in temperature the law does not hold. It is not even approximately true under conditions such as obtained while the data was taken

from which Fig. 23 was constructed. In this figure the curve is almost a straight line. This is due to the fact that the rate of loss is much more nearly uniform under these conditions than would be possible if the law held true. The law actually holds true for differences of temperature not exceeding 20° C. Other than for this range, however, there is no law which applies to the energy loss of any body subjected to radiation, conduction, and convection losses simultaneously.

To compute the radiation losses from a body under ideal or "black body" conditions it is customary to use the following formula, which is known as the Stefan-Boltzmann Law:

$$E = K(T_1^4 - T_2^4),$$

where E = the total energy;

K = a constant;

T_1 = absolute temperature of the body;

T_2 = absolute temperature of surroundings.

This law may be applied to any body subject to radiation losses only. The amount of energy lost in any practical case will be in proportion to a constant K , which must express the effect of the nature of the surface from which energy is being radiated. The energy loss with any given body will be in proportion to the fourth power of its absolute temperature. The energy received from its surroundings will be in proportion to the fourth power of absolute temperature of the surroundings. Thus the *net rate* of loss of energy will be equal to a constant times the difference between the fourth powers of the absolute temperature of a body and of the absolute temperature of its surroundings.

73. Black Body Radiations. The technical term "absolute black body" refers to an ideal surface which acts as a perfect radiator or absorber of heat. It is possible to construct a piece of apparatus which will give the same *results* as would an "absolute black body" and such an arrangement is called a "black body."

Theoretically, the requirements for a "black body" are all met by arranging to have the radiations come through a small opening in a box kept at constant temperature, from a lampblack surface in the center of the box. Fig. 58 shows such an arrangement.

Suppose an insulated box be constructed as shown in Fig. 58 and the outside packed with ice. If A is a blacked surface in the middle

of the box the amount of radiations coming to it must equal the radiations from it if the temperature is to be constant. If *A* were a perfect black body it would absorb all the radiations from the walls *C*, *D*, *E*, *F*, etc., and then give off the energy again in new radiations. If, on the other hand, the surface *A* is not perfect, it will reflect those rays which are not absorbed and the total light coming from it will be the same. The nature of the surfaces in this case makes no difference in the amount of the radiations.

A lampblack surface very closely approaches the "black body" as an efficient radiating surface. At ordinary temperatures rough surfaces radiate better than smooth polished ones and glass much better than smooth metallic surfaces. A copper surface painted with "alu-

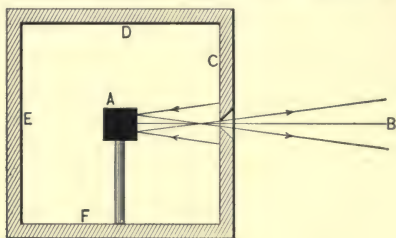


FIG. 58.

minium" flake paint is found to radiate much better than the bare polished surface of the copper vessel.

80. Relation of Visible Radiations to Heat Radiation. At low temperatures there are phosphorescent effects, in which light waves are given off without an attendant large loss of energy in the form of heat radiations. Notable cases of this in nature are seen in fish, sea-water, and the firefly.

In artificial illumination there have been many attempts to transform energy with apparatus at low temperatures, but no one has yet found and applied the firefly's secret. The "Moore Tubes" and other vacuum tubes are the best attempts that have thus far been found practicable. The temperatures in the region of the discharge are probably above 400°C ., but since there is so small a mass of gas being heated it is not easy to determine the temperature.

In all of the so-called incandescent lamps high temperatures are necessary to efficiency. What is desired is to have the largest possible amount of energy given off in the form of visible rays of short wave

length. Now it has been found by experiment that the energy given off by a body at fairly high temperatures is, in the main, given off by radiations of a limited range of wave lengths. This range of wave lengths in which energy is given off at maximum rate (or at which rays of maximum intensity are being given off) changes the value of the absolute temperature. (See Table XIII.)

Wein's Law is as follows: "As the temperature increases, each wave length in the spectrum diminishes in such a manner that the product of the wave length and the absolute temperature is constant." The formula for this may be written:

$$\lambda T = \text{a constant,}$$

where λ = wave length and T = absolute temperature.

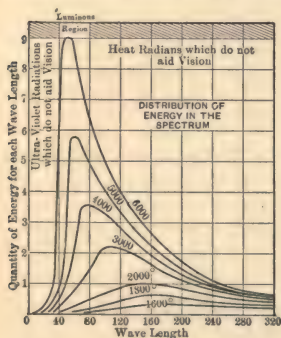


FIG. 59.

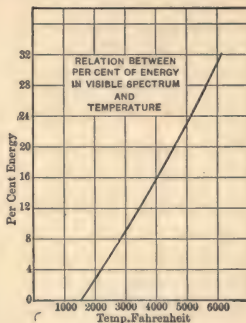


FIG. 60.

This law applies to each of the wave lengths and may therefore be applied to the wave length of maximum intensity. That is, it may be applied to the wave length at which energy is being given off at maximum rate, therefore,

$$\lambda_{\max} T = \text{a constant.}$$

This same idea is better conveyed by an inspection of the curves in Fig. 59, which show the energy radiated per second by bodies at different temperatures and shows the intensity or quantity for the various wave lengths. The area inclosed by the curves and the X axis

line is in direct proportion to the energy given off per unit area of the radiating body per unit of time.

It will be noticed from this curve that the higher the temperature the larger the relative area in the visible part of the spectrum. Applying this conclusion to the practical problem of incandescent illumination it follows that the higher the temperature at which a lamp is operated the greater will be its efficiency. The function of such a light is to transform its heat energy into radiant energy of a limited range of wave length.

Carbon lamp filaments may be operated at very high temperatures, but above 1900°C . the rate at which the carbon sublims is so great that it is not practicable to use the higher temperatures. The sublimate is deposited on the glass bulb and soon blackens the lamp if the lamp is operated at too high a voltage and temperature. Tantalum and tungsten do not sublime below their melting-point, so that they may be operated at higher temperatures than carbon and therefore are more efficient as lamps. Standard "Mazda" lamps of an efficiency of one watt per C.P. are operated at about 2300°C ., while the newer "Mazda" lamps, filled with inert gas (nitrogen or neon), introduced in 1913 are operated at about 2700°C .

81. Insulation Devices. The problem of keeping cold things cold and hot things hot has always been a live one. In cooking it is necessary that the food be maintained at a definite temperature for a given time until certain bacterial, mechanical and chemical changes have taken place in the structure and composition of the food. It formerly was true that no one thought much about the heat which is lost from cook-stoves. So common has been the practice of using the stove for both heating and cooking that an "insulated stove" has only lately begun to be a marketable article.

We now have "fireless cookers" in which food previously heated to the cooking temperature is placed. The device is provided with insulation to prevent loss of heat by the vessel in which the cooking is taking place. An early form known as the "hay cooker" was made from a box or pail padded on the inside with a hay-filled lining. After the covered dish containing the food was placed inside, another pad was placed on top of the dish and a

close fitting cover added to make a tight joint between the lining at the side and the top pad. This crude form has proved unsatisfactory for cooking many articles, because the success of the operation depends upon preventing a drop of more than a very few degrees.

Electric and gas "fireless stoves" are now being introduced in which the insulated chamber receives enough heat from the resistance coils or from a gas flame to equalize the losses of heat through the insulation. Very hot soapstones are also introduced in some cookers to provide a store of energy from which to supply the losses without cooling the food.

To store liquid air, Professor Dewar constructed a glass flask with a double wall. He exhausted the air from between the walls and silvered the inner surfaces of the vacuum chamber. The vacuum prevents convection and conduction through what would normally be an air-space. The only conduction loss is from

the top, where the inner and outer walls join. The silver produces a mirror surface on the two inner walls. The mirror surfaces reflect outward the incoming radiated heat rays without allowing the surfaces to absorb them and thus they reduce the gain in heat energy by radiation to a minimum. The gallon-size Dewar bulbs will keep liquid air for two weeks or more. The construction is shown in Fig. 61.

Commercial forms of this flask variously known as "Thermos bottles," "vacuum bottles," etc., are in common use.

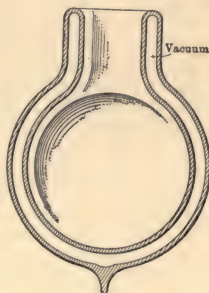


FIG. 61.—Dewar Bulb.

REVIEW PROBLEMS, CHAPTER IX

20. Good practice allows approximately 1 Kw. per square foot to be transmitted through an iron boiler tubing $\frac{1}{4}$ in. thick. What difference in temperature must exist between the two surfaces?

21. Good practice in condenser tubes allows a maximum of $\frac{1}{2}$ H.P. per square foot to be absorbed. What thickness between the two surfaces must be assumed to exist if the temp.dif. = 40° F.?

22. 107° C. steam gives up .073 Kw. per square foot through a bronzed cast-iron pipe to air at 20° C. What was the apparent thermal resistance of this material if it was $\frac{1}{4}$ in. thick?

23. 153° C. steam gives up .170 Kw. per square foot per hour through cast iron to air at 20° C. What was the apparent thermal conductance of this material?

24. The conductance of pasteboard is given as .00045 in cm. cube—calorie—degree C units (C.G.S.). Compute the coefficient in British units.

25. Compute the conductance in Prob. 24 in thermal mhos.

26. Compute the thermal resistance in Prob. 25.

27. Disregarding the effect of frost and assuming that the air in contact with the surface is at the temperature of the mass of air on the outside, compute the B.T.U. lost per hour through a plate-glass window $\frac{3}{8}$ " thick and $8' \times 12'$ in area. Temperature inside 70° F. Temperature outside 0° F.

28. Kent's Hand-book gives the conductance for asphalt-cork composition at 32° F. as .484 B.T.U. per hour. Compute the conductance in thermal mhos.

29. Enter the value given in Prob. 28 for asphalt-cork in Table XIV and compute the other constants.

30. Ground cork is given by Kent as having .250 B.T.U. per pound conductance. Record it in Table XIV, computing the proper value to go in each column.

31. Compute the heat lost per square foot of area per degree F. difference in temperature through a wall made up as follows: $1\frac{3}{4}$ ins. matched boards, 4 ins. of ground cork, $1\frac{3}{4}$ in. matched boards. Neglect the effect of paint, tarred paper, etc., which would regularly be used in this construction work.

32. Kent's Hand-book shows six values of the conductance in British units of asbestos. The value at 32° F. = 1.048, at 212° F. = 1.346, at 392° F. = 1.451, at 572° F. = 1.499, at 752° F. = 1.548, and at 1112° F. = 1.644.

Plot a curve showing the effect of temperature on the conductance of asbestos. State what this curve shows.

SUMMARY, CHAPTER IX

There are two processes by which heat energy as such may be transferred.

1st. **CONVECTION**, in which a part of a mass of fluid receives energy by conduction, then the mass with its heat energy is carried to a new location by currents which are set up, and finally gives up the heat to a colder body.

2d. **CONDUCTION**, in which the heat is passed on from adjacent layer to adjacent layer of particles without any relative motion of the masses of which the body is composed.

$$\frac{t_1 - t_2}{\text{watts}} = \text{thermal ohms} \left(\frac{\text{pressure}}{\text{quantity rate}} = \text{resistance} \right).$$

$$\frac{1}{\text{thermal ohms}} = \text{thermal mhos (conductance)}.$$

There are three ways of giving the constant from which conducted heat may be computed.

In thermal mhos (unit of conductance).

In C.G.S. units (usually referred to as coefficient of conductivity).

In British units (also referred to as coefficient of conductivity).

RADIATION is a process in which the energy is transferred as an ether vibration.

INSULATION of bodies is undertaken to prevent the transfer of heat. Poor conductors are used. A vacuum is a perfect preventative for conduction, and convection. Radiation is reduced by having a mirror surface on the body to be protected.

CHAPTER X

FUNCTION OF THE REFRIGERATOR PLANT

82. Household Refrigeration. The student already knows that the simple plan of using ice is the cheapest and most common way of keeping small quantities of perishables cool. There are two requirements only. First, an insulated compartment in which to store the goods, and second, an adequate supply of ice. The heat entering the chamber is taken up by the ice. The added heat energy causes the ice to melt. Ice is usually supplied at its freezing-point, 32° F., therefore every 144 B.T.U. which reach the ice melt a pound of it. The resulting water which contains the heat flows away in the waste pipe. The metal or tile lining is usually several degrees above the temperature of the ice, and so each pound of water takes up a few more B.T.U. from the walls of the chamber before it passes out.

Thus if the temperature of the water was 40° as it left the refrigerator and the ice as introduced was at 30° F., we would compute the heat taken from the cold chamber per pound of ice as follows:

Assume the specific heat of ice	=	.46
Heat taken up in rising from		
30° F. to 32° F.	=	$.46 \times 2$
	=	.92 B.T.U.
Latent heat taken up	=	144 B.T.U.
Sensible heat of water above 32° F.	=	8 B.T.U.
Total	=	153 B.T.U.

If the heat gained were all *conducted* into the refrigerator, then the amount of heat entering would be in proportion to the difference in temperature between the outside and the inside. This is not the case, however, as cracks and the drain pipe always allow a chance for some convection currents to bring in warm air. There are, also, losses due to the heat added while articles are being moved in or out of the storage space, and to changes in humidity. These irregular conditions make it difficult to compute the losses in advance, with accuracy.

By computing the heat absorbed by the ice or refrigerating machinery under varying conditions, the losses may be analyzed.

83. Mechanical Refrigeration. Most mechanical refrigerating plants are so arranged that heat is continually withdrawn from the cold-storage room by the evaporation of an extremely volatile liquid. In other words, the body or room to be cooled continually supplies heat to evaporate a cold volatile liquid which is continuously supplied by the refrigerating plant. The latent heat of vaporization is not quite all of the heat added to this volatile liquid, because its boiling-point is usually so low that some sensible heat is added to the gas formed by the evaporating liquid after evaporation has taken place.

The way this is accomplished is illustrated by Fig. 62, which shows a so-called *compression-type* refrigerating plant. A steam power plant is shown, the steam engine of which is driving the ammonia compressor. The compressor is doing mechanical work upon the cool ammonia and compressing it to 175 lbs. pressure. This would result in a very hot gas leaving the compressor if measures were not taken to keep the compressor cool. It is necessary to water-jacket the compressor to keep the cylinder from being overheated by the gases. These hot gases are next led to the condenser. Here they pass through tubes which are cooled by circulating water. Since the ammonia is under high pressure, the boil-

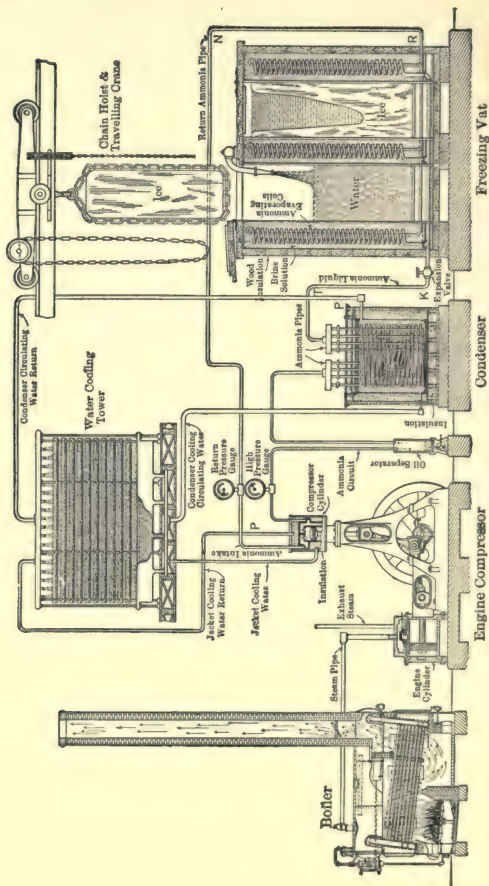


FIG. 62.—Sectional View of Compression-type Refrigeration Plant.

ing-point, and consequently the point of liquefaction is at a very much higher temperature than under atmospheric pressure. The condenser water cools the ammonia to its point of liquefaction. After the water has taken out the latent heat and changed the ammonia to a liquid, the water cools the ammonia further until it has nearly reached the temperature of the circulating water. By this process the heat is really taken out of the refrigerating plant and carried away.

This fairly cool liquid might still be further cooled by the use of an interchanger. The interchanger would be inserted in the piping at *TK* and the piping from the evaporator coils *RN* would be rearranged to allow the cool gases coming from the evaporator to pass upward over pipes *TK* containing the liquid ammonia under pressure. The cold gases would take up some of the sensible heat of the liquid entering the evaporator and thus increase the heat absorbed in the evaporator per pound of liquid circulated.

In the evaporator, the liquid under 175 lbs. pressure is allowed to pass through the valve at *K* into the expansion coils in the brine tank (or freezing vat.) The compressor suction keeps these coils fairly well freed from gaseous ammonia so that a pressure of about 28 lbs. gauge is maintained. The boiling-point at this pressure is very much reduced, so that the liquid quickly evaporates, taking its latent heat from itself and the adjacent metal. This vaporization cools the ammonia and the adjacent piping to approximately 15° F. If the piping were made of a perfect insulating material, the liquid would not all change to a gas, but a part would merely be cooled to its boiling-point at 28 lbs. pressure, 15° F., by the evaporation of the remainder of the liquid. Actually, the piping is a good conductor of heat and is usually in contact with brine, so that the liquid is all quickly changed to gas. The gas itself in most plants takes on enough heat to raise its temperature several degrees above its boiling-point before it leaves the evaporator.

In Fig. 62 the gas is shown to be returned directly

to the compressor. If we could replace the ammonia with a liquid which could be purchased cheaply and which could be allowed to evaporate into the air, we would not need any parts in a refrigerating plant other than an evaporator. The escaping gas would then carry away the heat in precisely the same way that the waste water carries the heat from an ordinary ice chest.

We will see in the following section how it is possible to avoid any waste of ammonia and still have the energy carried away through the waste pipe of the condenser and thus conveyed away from the plant.

84. Energy Flow through a Refrigeration Plant. In Fig. 63 is shown the *energy flow* through a 50-ton (of ice per day) plant. The computation is based upon the energy flow per ton of ice produced. By reference to the diagram it will be seen that 166 lbs. of coal of 13,620 B.T.U. per pound energy content would be required to deliver the 63 H.P. hours of mechanical energy required to make a ton of ice. This energy is used to compress the ammonia sucked out of the evaporator. In the compressor, a very large quantity of oil is used to fill the clearance. We might expect to have adiabatic compression so far as the space available for the gas affects the action, for we have no clearance. If the exhausted gases were compressed adiabatically they would leave at a rather high temperature and at a pressure of 175 lbs. The presence of so much oil and the fact that the walls are kept cold by the water jacket prevents any considerable rise in temperature and more nearly isothermal compression results. Since no internal heat is added during isothermal expansion, the work done is decreased by the use of a water jacket and consequently the efficiency of the cycle is increased. The diagram shows 145,000 B.T.U. carried away in the jacket water and oil.

From the compressor, the gas is conducted (first through an oil separator which is not shown and then) to the con-

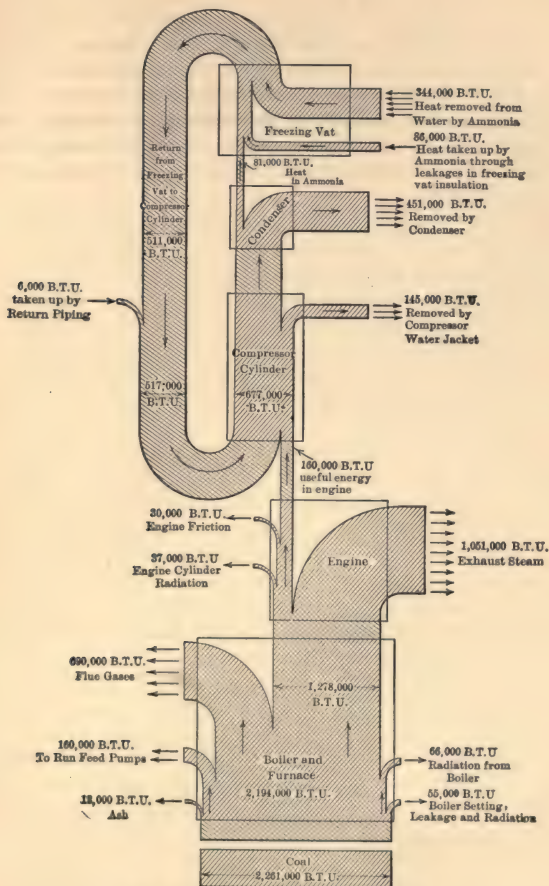


FIG. 63.—Energy Diagram for Fig. 62.

denser. Here it is cooled to its saturation temperature at 160 lbs. pressure, liquefied and cooled below the boiling-point. This is accomplished by taking out the sensible heat in the superheated gas, its latent heat of vaporization, and some of the sensible heat of the liquid. In all, 451,000 B.T.U. are so taken out. This quantity of heat leaves the plant at this point in the circulating water which is thrown away.

In the evaporator coils, into which the liquid ammonia next goes, the latent heat of fusion is taken out of the water and given, through the walls of the piping, to the ammonia to supply its latent heat of vaporization. In leakage losses, and in useful work, we have a total of 430,000 B.T.U. extracted from the freezing vat. The gaseous ammonia starts back toward the compressor at a temperature of 15° F. and receives roughly 6000 B.T.U. which are conducted or radiated in through the piping.

The exact manner in which the energy is evicted from the plant (or, speaking non-technically, the way the cold is produced) is by arranging for the circulating water to carry away heat from the condenser and compressor. The evaporator or the freezing vat can absorb only a limited amount of heat, namely the quantity that the liquid ammonia, delivered to the evaporator, can absorb in evaporating and circulating out as a gas. The ammonia, which is used over and over again, therefore, merely carries the heat from the evaporator to a more convenient and economical point to reject it, namely to the condenser.

85. The Steam Cycle and the Ammonia Cycle Compared.

It will be seen from the foregoing discussion that the ammonia goes through a cycle, time after time, which much resembles that of the water in our Figs. 38 and 39. We have a condenser which serves the same purpose in both cases. We have an evaporator in Fig. 62 which does a very similar service to that performed by the steam boiler in Fig. 38.

Finally, we have a compressor cylinder much like the engine cylinder of Fig. 38.

The latent heat of vaporization and the sensible heat of the gas, due to its being superheated, are taken out in the ammonia condenser. The only points of difference between the action of the ammonia condenser and that of the steam condenser are, first, that the pressure is much higher in the former than in the latter; second, that the temperature is much lower in the ammonia condenser; and third, superheated ammonia gas instead of a wet mixture of steam and water is liquefied.

In the ammonia evaporator, the liquid has the latent heat of vaporization added just as in a steam boiler water has its latent heat added. The liquid not only boils, producing a saturated gas, but the gas is also superheated either by passing through the warmer piping in the evaporator or by the piping of the circuit returning to the compressor. The steam boiler in a small plant usually starts with the liquid far below the boiling-point and does not superheat the steam. Thus the function of each piece is the same, but they work at different temperatures and pressures. The range of temperature relative to the boiling-point is different for the two. The liquid in the steam boiler is pumped in and, because of the change of pressure, undergoes a change in boiling-point. In the evaporator the liquid is admitted through a valve with a reduction of pressure and a consequent lowering of the boiling-point.

The action in the compressor cylinder is the reverse of that which takes place in the steam cylinder. In the engine, hot gas admitted under high pressure does work, expands doing more work, and is exhausted as a wet mixture at a reduced temperature and pressure. In the ammonia compressor, ammonia at a low pressure has work done upon it which results in a gas being delivered by the compressor at an increased pressure and temperature.

While the direction of flow of the working medium in

the refrigerating cycle is the same as that of the steam cycle in the power plant, the pressure changes are in a reverse order.

The conditions are almost reversed in the two plants in respect to the energy relations throughout the cycle. In the steam plant the object is to add all of the energy possible to the working medium in every part of the plant save one, the engine, where it is intended to give out as much as possible. In the refrigerating plant the object is to keep energy from entering the working medium and to reject it from the working medium as much as possible in every member except the evaporator, where the working medium is allowed to receive as much energy as possible.

The steam plant, in other words, conserves energy in its function of transforming energy and the refrigerating plant does work in order to give off energy in as large quantities as possible.

In the compressor cylinder, just as in the engine cylinder, adiabatic conditions would result if perfection could be attained. Therefore the first steps in computing the theoretical performance of a compressor is to apply the formula for adiabatic compression to the cylinder. Oil is used in the cylinder to fill the clearance at the end of the stroke and thus enable the compressor to discharge very nearly all of the gas drawn in during the suction stroke. The effect of the oil and the water jacket is to keep the working medium cooler than the temperature which would result from adiabatic compression. The cooler gas does not produce as much pressure as would result from adiabatic compression. Accordingly the engine that drives the compressor will not have to supply as great a force to compress the gas, and it will therefore do less work per pound of working medium. Whatever saving of work follows from doing less than would be required under adiabatic conditions also results in a second saving

to the plant. If the energy per pound given to the gas is reduced, the condenser is not required to take out so much energy while changing a pound of gas to liquid. The condenser will then have less work to do and can be built smaller.

86. Computation. Since mechanical refrigeration competes with ice it is usual to compute the efficiency of a plant by stating its ice-making capacity under given conditions. The basis of the computations of the duty and performance of a refrigerating plant is usually the production of one ton of ice. This is true whether the plant is used for ice-making or for any other purpose.

For example, so-called "sharp freezers" are rooms used to quickly cool and freeze food products like fish, meats, etc., which are to be kept for a long time or shipped long distances. For these rooms, an ice-making capacity considerably greater than the weight of goods to be frozen per hour is necessary. The heat capacity of fish is roughly .8 as much as that of water in both the solid and the liquid state. Therefore, to cool fish from $+75^{\circ}\text{F.}$ to $+10^{\circ}\text{F.}$ would require approximately $(75-32) \times .8 + .8 \times 144 + 22 \times .4 = 148$ B.T.U. per lb. Practically, this figure is only a rough approximation, because it is usual to glaze fish in a coating of ice, and this adds to the weight to be frozen. If 200 B.T.U. are required per pound of fish, the equivalent ice-making capacity required is $\frac{200}{144} = 1.39$ lbs. of ice; that is, a plant which would handle under the above conditions 5 tons of fish per hour would under theoretically ideal conditions freeze about 6.95 tons of ice.

To keep theaters and auditoriums cool in tropical countries and even in New York City, refrigerating plants have been installed. Such a plant, just as in the case of a sharp freezer, would be rated in terms of its ice-making capacity, even though no ice is made for use *as ice*. Incidentally, there is some ice made and several other functions per-

formed by a plant of this character. Actually some moisture is frozen out of the air.

The bacteria and particles of putrefied matter are usually taken out by washing the air, thus keeping it free from odor. The air is changed often enough to allow each person at least 300 cu.ft. per hour. A person at rest gives off about 400 B.T.U. and there must be air enough removed to take this much heat away if the room temperature does not rise.

Problem 1. If 100 lbs. of ammonia are circulated through the plant shown in Fig. 63, what is the temperature of the gas as it enters the compressor if its temperature as it leaves the vat is 15° ?

Problem 2. In the above plant, how many lbs. of ice can be made from water at 72° F. per lb. of coal (14,000 B.T.U.) burned?

Problem 3. If the temperature of the 100 lbs. of ammonia drawn into the cylinder of the compressor of Fig. 63 was 60° F. what would have been the exhaust temperature under adiabatic conditions?

Problem 4. If the gas in the previous problem was compressed from 28 lbs. gauge pressure and a density .133 lb. per cu.ft., what must have been its density at exhaust if the pressure was 175 lbs. gauge?

Problem 5. What must have been the pressure of the ammonia in Prob. 3 if compressed isothermally from 28 lbs. gauge?

Problem 6. How many horse-power hours of work must the engine in Fig. 63 develop per ton of ice frozen from water at 72° F.?

87. The Absorption Refrigeration Plant. The absorption system of refrigeration is like the compressor system in that the condenser and the evaporator, or cooler, are common to both, and perform the same duty under almost the same conditions in both cases. The absorption plant differs from the compressor plant in that the function of the compressor of the latter is performed by two or more parts in the absorption plant.

The compressor may be considered to be primarily engaged in sucking out the ammonia from the evaporator in order that the boiling-point of the ammonia in the evaporator may be kept low. This task of keeping the evaporator or cooler free from ammonia is done by an absorber

in the absorption plant. Its action depends upon the property of ammonia which causes ammonia to dissolve in cold water in large quantities. A ratio of 1000 volumes of ammonia to 1 of water is possible.

In an absorption refrigeration plant, a second piece of equipment is necessary in which the solution of ammonia pumped from the absorber may be heated and the ammonia again driven off under high pressure. This piece is called a generator and is simply a tank heated by a steam coil placed inside of the tank. A pressure can be maintained upon this coil in just the same way as in a steam boiler.

88. Cryogenics. The name by which FREEZING MIXTURES are technically known is cryogenics. We are all accustomed to use common salt (NaCl) and ice to cool iced food, and confections. The action depends upon the fact that the freezing-point of a solution of salt in water is very much lower than that of either the pure water or the salt. The solid salt mixed with solid ice, both being at a temperature well below 32°F. , produces a liquid solution of the ice and salt. A mixture of 3 parts by weight of snow at 32°F. and 1 part of common salt at 32°F. if placed in an insulated calorimeter will rapidly melt into a mush with a resulting temperature of -4.5°F. This is the freezing-point of the salt solution.

This is by no means the lowest temperature which can be obtained by freezing mixtures. A calcium chloride solution (CaCl_2) is used for brine in some cold storage plants because it is reasonably cheap and has a much lower freezing-point than common salt (NaCl) solution.

If we mix 7 parts of snow at 32°F. with 10 parts of crystalline calcium chloride ($\text{CaCl}_2 + 6\text{H}_2\text{O}$) the temperature will drop to -66.8°F.

NaCl will continue to be used in freezing mixtures in place of the more expensive salts which produce the lower temperature because the quantity of energy which may be absorbed by outside bodies is not in proportion to the reduc-

tion in temperature produced by the cryogen. In many cases the more snow used per pound of salt the greater is the amount of energy released per pound of salt and per pound of mixture.

89. The Production of Low Temperatures by Mechanical Means. The refrigerating plants discussed in the previous sections are adapted to maintaining temperatures as low as 10° or 15° F. When lower temperatures are required it is necessary to use a different gas than ammonia for the working medium. With air-refrigerating plants it is possible to reduce the temperature many degrees below zero, the plant being arranged in the same general way as that shown in Fig. 62. Such plants have rather small commercial application and they do not recommend themselves to scientific research.

The study of extremely low temperatures which has resulted in the production of liquid air, liquid hydrogen, liquid helium, and other rare gases, has only been possible with a modified type of equipment. Fig. 64 shows a lecture-room equipment for making liquid air which illustrates many of the principles involved in low-temperature work. A tank or other source of supply for air or other gas under a high pressure is necessary. This gas is led through a precooling coil in D_1 .

D_1 contains a supply of cracked ice or snow and is intended to cool the air to approximately the freezing-point of water. The air may next be led through D_2 , which may contain a freezing mixture capable of cooling the air to -20° or -30° F. The air is then led into D_3 , which is a carefully insulated chamber. The air travels downward, still under high pressure, through the coils of copper tubing to a needle valve at the bottom. This valve may be adjusted from the outside by turning the knob F .

In this apparatus, just as in the refrigerating plant, the working medium under pressure and previously cooled is allowed to expand at a valve. During adiabatic compres-

sion a large amount of heat is taken out. The gas expands nearly to atmospheric pressure, when it comes through the valve. While it is expanding work is done against the atmosphere and perhaps against intermolecular forces. The energy to do this work is taken from the gas itself and thus the gas is cooled. (See *Physical Review*, Vol. XXIX, No. 3,

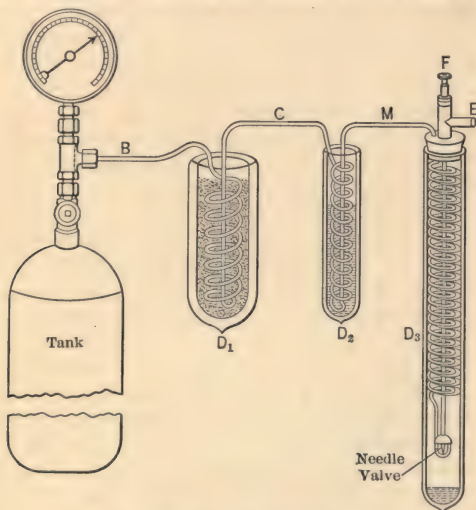


FIG. 64.—Air Liquefier.

Sept., 1909, pages 258–292.) This cold gas rises and comes in contact with the copper tubing which supplies air to the valve. The tubing and the compressed gas in it are cooled by the gas as it rises to escape toward *E*. The next gas to reach the valve will arrive somewhat cooler, therefore, and, after doing work against the atmosphere and against intermolecular forces, will expand and be at a lower temperature than the first gas to pass the valve. This

colder gas will in turn be forced upward over the coils and will further cool them. This continual cooling of the gas in the pipe goes on until the gas that comes from the valve expands and cools to a temperature at which the gas becomes a liquid. Then a part of the gas is liquefied and collects in the bottom of the chamber and only a part returns upward over the pipes to keep them cold. When this condition of equilibrium is reached, liquid continues to accumulate in the bottom of the vessel so long as the supply of gas under pressure is maintained.

The arrangement of coils shown in D_3 is the essential feature of what is known as the REGENERATIVE METHOD. The student will see that this is simply an application to the problem of low temperatures of the countercurrent principle, which has already been observed in distillation, in the steam boiler, and in condensers generally. By having the coil in D_3 sufficiently long the air which comes out at E may be made to give up its "store of cold" so completely as to be warmed to practically the same temperature as the gas in M .

D_1 and D_2 are not absolutely essential to the production of even such low temperatures as are required to liquefy air, but they increase the efficiency of the process under certain circumstances. If hydrogen is to be made liquid in D_3 , it is practically necessary to put liquid air in D_2 to cool the supply of hydrogen which will flow through B , C and M .

Many attempts have been made to replace the needle valve with an engine or turbine which would use the gas adiabatically to do external work in addition to that required to expand it against atmospheric pressure. If adiabatic expansion could be obtained in this way, a much greater quantity of liquid air per pound of air circulated could be obtained. It has been successfully demonstrated that this may be done, but such an arrangement has not come into common use.

The pressure used in commercial liquid air machines is frequently in excess of 3000 pounds per square inch. To compress the air to such pressures is impossible in a single stage. Two, three-, or four-stage compressors are therefore used. The air travels from the first stage through water-cooled coils in what is called an intercooler to the second and smaller cylinder. After being further compressed in the second cylinder it goes through a second set of water-cooled pipes in the intercooler. It then goes to the third cylinder, which is still smaller than the second. Between the third and fourth cylinder (if a four-cylinder compressor is used) the air is again passed through the inter-cooler. After leaving the fourth and smallest cylinder the air must be treated in a tank or bomb to take out all moisture and CO_2 . It is then ready to be passed through a pre-cooler and into the liquefier. The CO_2 is usually taken out by caustic potash and the water by caustic soda, calcium chloride, or other suitable compound. Considerably over a quart of liquid air per H.P. hour of work done may be obtained in a modern liquefier of the regenerator type.

The difference between the quantity of heat energy in 1 lb. of a gas as it enters at M , Fig. 64, and the energy in the pound of gas as it leaves at E is all of the energy that can be withdrawn from within the apparatus. If we assume a perfectly insulated chamber, and no losses within the apparatus due to friction in the piping and valve, or due to any other cause, all of this difference in energy may be taken from additional air admitted at M and liquid may thereby be produced. Since the ideal apparatus takes air at M and delivers it at E at the same temperature but with a higher volume and a lower pressure, the energy taken from the interior of the apparatus may be computed by one of the formulæ for isothermal expansion on page 210.

These formulæ show that the energy left in a perfect apparatus by a pound of air would be in proportion to the

absolute temperature at M and the logarithm of the volume ratio at M and at E . It follows that in theory, precooling at D_1 and D_2 in Fig. 64 tends to reduce the efficiency except as it is justified by mechanical limitations of the apparatus and the fact that such precooling leaves less energy to be taken from that portion of the gas which is liquefied.

The energy left in the liquefier may be computed for the actual conditions where the absolute admission temperature at $M(T_M)$ is higher than that at $E(T_E)$, by subtracting from the work done when isothermal expansion takes place the energy to heat the gas from T_E to T_M , thus:

$$W = RT_M \log \frac{V_2}{V_1} - (T_M - T_E)C_P.$$

Problem 7. Compute the total work which would be done against the atmosphere by a pound of air if it expanded from 3000 lbs. per square inch to 15 lbs. absolute? Assume also that the temperature before its expansion takes place was -180°C . and as it escapes from the apparatus in Fig. 64 at E it was at -5°C .

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}.$$

The volume of air at 3000 lbs. pressure (V_2) at a temperature of -180°C . would equal

$$\frac{14.7 \times 12.39}{273} = \frac{3000 V_2}{93};$$

$$V_2 = .0207 \text{ cu.ft.}$$

V_3 = the volume of air at -5°C . and 15 lbs. would be

$$\frac{14.7 \times 12.39}{273} = \frac{15 V_3}{268}.$$

$$V_3 = 11.92 \text{ cu.ft.}$$

The total work done against the back pressure will be $(V_3 - V_2)$ in cubic feet $\times$ pressure in lbs. per square foot or $11.90 \times 15 \times 144 = 2570 \text{ ft.-lbs.}$; this equals 3.3 B.T.U. By how much does this result differ from the energy left in an ideally perfect regenerative liquefier with an admission temperature at M (Fig. 64) of -5°C .?

Problem 8. If 1 lb. of air under 2400 lbs. absolute pressure

passed through the tube M in Fig. 64 at a temp. of 20° F., came out at E at a temp. of 16° F., and no liquid was formed, does the heat energy leaving at E differ from that entering at M and if so compute the difference in amount.

Problem 9. If air is admitted to an apparatus similar to that shown in Fig. 64 at a temperature of $+5^{\circ}$ C. in the pipe M and leaves the pipe E at -5° C., what weight of the air admitted would be liquefied? Assume a specific heat of .17 in both cases, the latent heat as 51 and no other cooling effects.

Problem 10. What would be the total work required to compress 1 lb. of air from 70° F. adiabatically to 2000 lbs. pressure by the following stages:

First stage	75 lbs.	and pre-cooled to	60° F.
Second "	250	"	60° F.
Third "	750	"	60° F.

Problem 11. If a producer gas power plant with an efficiency of 20 per cent and a compressor of 90 per cent efficiency supply air to a liquefier which delivers 1 qt. of liquid air per horse-power hour, what weight of air is passed through the liquefier per horse-power hour? Assume the same amount of work done per pound as in the previous problem.

Problem 12. If in the previous problem the coal for the gas producer contains 14,000 B.T.U. per pound, how much liquid air per pound of coal was produced?

90. Insulation of Cold-storage Spaces. The secret of *maintaining* a low temperature lies in the means of insulating which are adopted. The use of insulating materials has already been referred to in the last chapter. It should be pointed out in this connection that every B.T.U. admitted to the cold space in a store room or in a piece of low-temperature apparatus must be taken out by the refrigerating machinery or by the melting ice or cryogen used.

The Dewar bulb shown in Fig. 61 illustrates a number of points in design which are worthy of attention.

First: It will be noticed that the only opening is at the top. The cold gases which are given off from the liquid contained in the bulb are usually more dense than the warm air outside and consequently do not promote convection currents. This is the case with either air, oxygen, or nitrogen.

This method of construction has sometimes been used to advantage in building cold storage rooms. By constructing solid walls on all sides, the goods may be taken in on the top floor and lowered by elevators to the proper rooms. Convection currents while the goods are being moved are thus minimized, and only the heat energy in the goods themselves, and such energy as is conducted through the walls, need be removed.

Second: Effective insulation requires that no moisture be conducted inward and deposited to close up the air spaces in the fibrous materials used as insulation. In the Dewar bulb this is effectually accomplished by the vacuum. In constructing refrigeration store rooms, courses of tarred paper are laid between matched boards, and brick, or cement walls are tarred to keep moisture from going inward to the cold walls. In making large liquid-air machines the apparatus corresponding to D_3 of Fig. 64 cannot be encased in a Dewar bulb as shown in the figure. However, the plan adopted by Prof. W. P. Bradley of Wesleyan University, who has made many of these machines, has been very similar. A double case of tin replaces the walls of glass and between these is packed hair felt. If the felt is thoroughly dry when introduced and the tin walls are then carefully soldered tight, no more air is admitted to the space filled by the hair felt, and therefore no moisture can be conveyed in.

Third: Radiation is prevented by placing a mirror surface on both inner walls. The outer mirror tends to prevent the propagation of the waves by the outer wall. The inner mirror reflects those reaching the inner surface. In ordinary refrigeration radiation losses are minimized by using opaque materials and numerous air spaces.

The pains taken in any commercial installation will depend upon the cost of the refrigeration effect required to carry away the excess heat. Any investment required to improve insulation must result in a decreased cost of refrigeration large enough to make the investment profitable.

REVIEW PROBLEMS, CHAPTER X

13. A small refrigeration plant which requires 100 H.P. hours per ton of ice, is operated by a motor-driven compressor. The ammonia enters the water-cooled compressor at 35°F. and leaves it at 145°F. It enters the condenser without further change of temperature and leaves as a liquid at 180 lbs. absolute pressure and 65°F. Without further change in temperature it entered the evaporator and dropped in pressure to 30 lbs. absolute pressure. The ammonia gas left the evaporator (freezing vat or congealer) at 25°F. 80,000 B.T.U. were lost from evaporator by radiation, conduction, and convection. Water was introduced into the cans at 60°F. and ice was withdrawn at a mean temperature of 24°F. The latent heat of ammonia under 30 lbs. abs. pressure = 556 B.T.U.

“ “ 180 lbs. abs. pressure = 449 B.T.U.

The boiling-point under 30 lbs. absolute pressure = 0°F.

“ “ 180 lbs. absolute pressure = 89°F.

Compute the following quantities in order:

(a) Heat taken out of the evaporator per pound of ammonia circulated.

(b) Heat given up per pound of ice made.

(c) Total heat to be taken away per ton of ice made.

(d) Total weight of ammonia which must have been circulated.

(e) Heat radiated, etc., from piping between evaporator and compressor.

(f) Total energy carried away by the circulating water of the compressor jacket. (Assume no significant quantity of heat to be radiated or otherwise carried from the compressor except by the ammonia gas and the jacket water.)

(g) Compute the energy carried from the condenser by the circulating water. (Assume no heat lost or gained except in the ammonia gas and the circulating water.)

(h) Finally, draw the energy diagram for this plant, placing upon it all of the results computed above and any other needed information.

14. Compute the useful work done in Prob. 13 by the compressor if 700 lbs. of ammonia per ton of ice had been circulated.

15. What would have been the compressor efficiency in Prob. 14?

16. How much water could have been frozen in Prob. 13 if the water had been taken in at 32°F. , and the ice delivered at 32°F. ?

17. Assuming that the laws for perfect gases apply, how much work would be done by a pound of hydrogen expanding adiabatically from 3000 lbs. to 15 lbs. absolute pressure? Temperature at M before expansion -27.5°C.

18. If the hydrogen in Problem 17 were heated after expansion at constant pressure to -27.5°C. how many B.T.U. would be required? (Assume the specific heat given in the table.)

19. Compute the energy that would be left in an ideal regenerative liquefier using hydrogen at 3000 lbs. and -27.5°C. and expanding it to 15 lbs. absolute pressure.

20. Draw an energy diagram for a plant operating under the conditions of Problems 10 and 11, page 263.

SUMMARY, CHAPTER X

The problem of refrigeration consists first in removing heat, and, second, in keeping it out.

The LATENT HEAT OF FUSION of ice is the chief source of cold in refrigeration. Ice by melting absorbs heat and takes it from the cold storage space when the water flows away.

In the MECHANICAL REFRIGERATING PLANT liquid ammonia or other suitable substance is made to evaporate in the piping in the cold room. In all the common commercial machines the latent heat of vaporization takes up the heat and the gas formed takes away the heat of vaporization plus some sensible heat.

By insulation, the heat conducted, conveyed, and radiated in may be greatly reduced.

The plant must take away all of the heat brought in with the articles to be refrigerated.

CRYOGENS, or freezing mixtures, are usually mixtures of two solids which melt into a solution of much lower freezing-point than that of either solid alone. The source of refrigerating effect is their latent heat of fusion.

LOW TEMPERATURES are obtained in practice by expanding a gas at a valve in an apparatus which keeps out the heat energy by using the counter-current or regenerative principle.

CHAPTER XI

INSTRUMENTS

91. Instruments for the Measurement of Temperature.

To measure temperature we usually employ an instrument known as a thermometer or a pyrometer. The action of these instruments depends upon some effect which accompanies a change of temperature. Illustrations of such effects are: the expansion of a solid, liquid, or gas, the change in resistance of an electrical conductor, the thermoelectric E.M.F. in a thermo-junction, or the difference in quantity of energy radiated because of the change in temperature.

When any effect is taken as a means of producing a reading in the instrument, the accuracy of the readings as indications of the true temperature will depend upon the uniformity of this effect with relation to the change of temperature unless some correction is automatically made. There are no effects known which are directly in proportion to the change in temperature. Thus the expansion of a substance is never uniform over any considerable range of temperature. At some temperatures a solid may even contract with increase of temperature. Therefore, either the scale of the instrument must be constructed in a way to correct for the irregularity of the effect, or the readings must later be revised to correct for the irregularity.

The linear expansion of a solid with an increase of temperature is often taken advantage of in portable thermometers and *thermostats*. Usually these instruments contain a rod or strap made of two thin strips of different

metals. One end of each strip is fastened to a rigid frame. The remaining ends are fastened together and to the recording mechanism. The two metals are so selected that there is a large difference between their rates of expansion. Upon change of temperature, one therefore becomes longer than the other, and since their two ends are fastened together, the one expanding the more bends the other over into a crescent shape. The end attached to the mechanism is thus made to move and to drive an indicator about a dial, in the case of a thermometer, or to close an electric circuit or open a valve, in the case of a thermostat.

A thermometer constructed in this way may be arranged to indicate a wide range of temperatures. The readings are only approximate indications of the temperatures.

For scientific purposes a thermometer is most often used over a short range of temperature, and frequently it is not so important to know just what the temperature is as it is to know what is the difference in temperature.

For accurate determinations of differences in temperature the amount of expansion of a liquid or a gas is ordinarily used. In cases where a fluid is used, either the change in volume or the change in pressure of the fluid may be used as a means of indicating the temperature change.

In the most common types of thermometers, liquids are encased in a bulb. To this bulb is attached a long stem and the change in volume is indicated by the motion of a thread of the liquid up or down the stem. Therefore, to indicate temperatures, the scale must be graduated so that lengths along it are in proportion to the change in volume. The length between any two marks, indicating two different temperatures, is the particular length of bore along the tube which will be filled by the liquid expanding out of the bulb when the temperature changes from the value indicated by the first mark to the value indicated by the second mark. The mercury thermometer and the

alcohol thermometer are of this type and are in universal use.

92. Mercury Thermometers. Every student who reads this text has probably seen and used mercury thermometers. The only new things which he needs to know about them are related either to their construction or to their scientific and technical use.

To make a mercury thermometer the first step is to select a stem of uniform bore. Upon this is fused a cylindrical bulb of a capacity to correspond with the range of the thermometer. By inserting the open end of the stem in mercury and heating the bulb, the air which it contains may be partially driven out, and upon cooling, the mercury will be forced in by atmospheric pressure to replace the air driven out. By inverting the bulb and heating again, some more air can be driven out and the space thus emptied filled with mercury. By repeating this process a number of times a sufficient quantity of mercury may be introduced to practically fill the space. The thermometer is then heated until the air is all driven out and the mercury expands sufficiently to fill the bulb and the stem. The top is then sealed off. When the mercury cools a vacuum is left above the mercury. Then the thermometer is laid away to age for from a week to a year, depending upon the accuracy of the instrument desired.

To calibrate this instrument two so-called "fixed points" are obtained. One is the freezing-point of water. This point is marked upon the thermometer in wax previously placed upon the stem. The position of the mark is determined by placing the thermometer in a mixture of ice and water and allowing the mercury to come to rest.

The second fixed point on a thermometer is the boiling-point of water under standard conditions of pressure. This point is marked in a way similar to the first. By enclosing the bulb and stem in steam under atmospheric pressure the position of mercury corresponding to the tem-

perature of boiling water may be located by a scratch in the wax. Graduations are then etched upon the glass by applying hydrofluoric acid.

On page 13 it is stated that these two fixed points on the Fahrenheit scale are respectively 32° and 212° . On the Centigrade scale they are at 0° and 100° .

In cheap thermometers the space between the boiling- and freezing-point is then divided into equal graduations, marked according to the system used; sometimes a uniformly graduated paper scale is attached at approximately the correct position. Good thermometers usually have the scale graduated on the glass stem, according to the system used. If a thermometer is to be used as a standard, the divisions between the freezing-point and the boiling-point must be made with some regard to the inequalities in the bore of the stem. It must be remembered that the calibration should properly be in units of volume, because the expansion of mercury is a volumetric effect and not a linear effect.

To find these inequalities and determine the value of the degree spaces at each portion of the stem, a small thread of mercury is broken from the main thread and is moved along the bore by short intervals, starting from one of the two fixed points. By the use of a microscope the length along the stem occupied by the thread is carefully observed for each successive position of the thread. By careful manipulation this short thread may be made to move along the whole length of the tube step by step, thus measuring off lengths along the bore which will contain equal volumes. These lengths are then subdivided into equal parts. The more steps taken in calibrating a given length the greater the accuracy. In this way errors due to inequality of bore and unequal volumetric expansion can be avoided at the intermediate points along the scale.

If the thermometer is to be calibrated for higher temperatures than 212° F., it may have other fixed points determined, such as the melting-point of sulphur or certain

salts. Yellow phosphorus melts at 43.3°C ., sulphur melts at approximately 115°C . and boils at 441.7°C ., sodium chloride melts at 774°C ., etc.

The advantages of mercury as a thermometric liquid lie in the facts that it is a good heat conductor, has a low specific heat, is easily seen even when the thread is very fine, does not wet the tube, does not cling to the glass, and has a practically uniform rate of expansion between 0°C . and 100°C . Its use is limited by the fact that it freezes at -38.2°F ., and that its vapor tension is excessive for temperatures above 1000°F . In fact if it is to be used for temperatures above 400°F ., it is necessary to admit nitrogen to the space above the mercury, before sealing off the stem, to prevent boiling and "bumping" at the higher temperatures.

In the preliminary report of the power test committee, A.S.M.E. Journal, page 1696, the following statements are made concerning thermometers:

"Standard thermometers are those which indicate 212°F . in steam escaping from boiling water at the normal barometric pressure of 29.92 ins. (referred to 32°), the whole stem up to the 212° point being surrounded by the steam; and which indicate 32°F . in melting ice, the stem being likewise completely immersed to the 32° point; and which are calibrated for points between and beyond these two reference marks. For temperatures between 212° and 400°F . the comparison of the thermometer should be made with the temperature given in Marks and Davis' Steam Tables, the method required being to place it in a thermometer-well surrounded by saturated steam under sufficient pressure to give the desired temperature. The pressure should be determined by a correct gauge, and the thermometer should be immersed to the same extent as it is under its working condition.

"A thermometer-well consists of a hollow plug threaded at the upper end and screwed into a threaded hole in the top of a horizontal pipe, the lower part extending vertically into the interior of the pipe as far, if practicable, as the center. The inside diameter should be slightly larger than the outside diameter of the thermometer tube and the well should be filled with soft solder for higher temperatures.

"For superheated steam the immersed portion should be fluted so as to increase the area of the absorbing surface.

"Thermometers are so readily broken that it is desirable in impor-

tant tests to have a sufficient number on hand that in case of accident the readings will not be interrupted. These spare thermometers should preferably be calibrated."

Every accurate mercury thermometer is made by hand methods. There is no known way of making the parts by machinery, as bolts, screws, etc., can be made. After they are made with care their value also depends upon the care and skill with which they are calibrated and aged.

The raw materials in a ten-dollar thermometer cost, at most, only a few cents. The difference in cost of high-grade materials and of cheap materials is very little. Thus in every stage in the making of mercury thermometers, the quality of the product and the cost are dependent almost absolutely upon the workmanship used upon it.

In Bohemia, girls make thermometers in large quantities. These are frequently so cheap that they may be had for a few cents a dozen. To the casual observer there is little difference between a 50-cent thermometer and a \$5 thermometer. The writer has recently been offered thermometers at 35 cents for which he has seen others pay \$2.

Since the value lies in the workmanship and since there is no easy way of telling at a glance the amount of skill and labor used in making the instrument, the problem of purchasing thermometers is a difficult one. There are a few reliable makers who guarantee each of their thermometers and do all in their power to keep the methods of making the instruments such as to enable them to exceed their guarantee.

The detail operations in the art of making thermometers may be varied greatly. Each maker guards his own process as a trade secret and will not explain any details other than those which are of advertising value.

There is a maker in Brooklyn, N.Y., who has an excellent reputation for making reliable thermometers. The only point which he will give out for publication is that the bulbs

on his standard thermometers are all made from a single pot of glass made for him in Jena, Germany, in 1889.

The composition of this glass is said to be such that it ages quickly and then upon repeated expansion it always returns approximately to the original condition. The glass contains no lead, but has 7 per cent of oxide of zinc. This maker estimates that he will have enough glass in this single pot to last a lifetime. Another advantage in using the same glass for all the bulbs lies in the fact that the rate of thermal expansion of all thermometers of this make is the same, and after the thermometers are aged they will continue to check one against the other for an indefinite length of time. Since practically all of the volume of mercury is enclosed in the bulb, the readings of the thermometer are almost entirely dependent upon the expansion in the bulb. For this reason only the bulb needs to be made of the special glass, as the expansion effects in the stem have no significant effect upon the readings.

93. Alcohol Thermometers. Alcohol thermometers are used chiefly for low temperatures where there is danger of the mercury freezing. In case a large thermometer for show windows or for outside use in a public place is desired, alcohol is somewhat more convenient because it has a larger coefficient of expansion, and therefore, gives a larger visible effect for the same quantity of liquid used in the bulb and for the same change in temperature. It is always calibrated against a mercury standard or gas standard thermometer. Turpentine, pentane, and various other liquids are also occasionally used to replace the mercury. Alcohol thermometers are not adapted to use for temperatures above the boiling-point of alcohol, 78°C .

94. Sensitive Thermometers. By making the bore of the stem very fine as compared to the size of the reservoir at the bottom, it is possible to make a thermometer which will be very sensitive to small changes in temperature. In this way thermometers are constructed which

read differences in temperature to a thousandth of a degree F.

To avoid making the stem very long, a large bulb is blown at the top of the stem of the thermometer and part of the mercury is placed in the upper reservoir when the range of temperatures is higher than can be read otherwise. In this event only differences in temperature are indicated correctly.

95. Gas Thermometers. Thermometers used for ultimate standards in extremely accurate scientific work are of the gas thermometer type. The apparatus used is similar in principle to that shown in Fig. 20. When extreme accuracy is desired, however, a great many refinements are added. If in Exp. H 1-3, page 86, we assume that we know the rate of expansion of the air in the bulb, A , and the rate of expansion of the glass, and if in addition we know the pressure required to keep the mercury at M , at 0°C. , we will be able to determine the temperature of the bulb, A , under any other set of conditions.

In writing up the computations on page 88 the data marked 1 was not used. From this we may compute the true room-temperature as follows:

$$P_{t^{\circ}} = P_0 \left(1 + \frac{1}{274} t^{\circ} \right)$$

where t° is the temperature centigrade. Substituting,

$$15.42 = 14.18 \left(1 + \frac{t^{\circ}}{274} \right);$$

$$274(1.26) = 14.18 t^{\circ};$$

$$t^{\circ} = 24.3.$$

Now this result does not work out to agree with the thermometer reading taken at the time. The difference may be due in part to the fact that thus far no correction has been applied to this first reading for the expansion of the mercury. The thermometer used for the measurement of the room temperature should be charged with the remainder of the deviation in results.

The only practical limits to the use of this apparatus as an air thermometer are the melting-point of the glass, the temperature at which the air is liquefied, and the point where oxidation of the glass would begin. By using nitrogen instead of air and by using porcelain or quartz in place of glass, the upper limit may be raised many hundred degrees.

There is no permanent gas whose rate of expansion is absolutely uniform and in direct proportion to the temperature over a wide range. The factors of correction, however, for hydrogen and nitrogen have been determined with great accuracy and the hydrogen thermometer is the standard for temperatures below 200°C . and the nitrogen thermometer for temperatures above 200°C .



FIG. 65.—Resistance Pyrometer Bulb.

96. Pyrometers. There are two common types of pyrometers in commercial use in this country: the resistance pyrometer and the thermo-junction pyrometer.

The types will be well enough understood from the description of one make of each type given in the following paragraphs.

Fig. 66 shows the arrangement of parts in the Leeds & Northrup resistance pyrometer. This instrument consists essentially of two parts. First: a resistance coil of platinum or other refractory metal protected by a long tube of metal, porcelain, or quartz. This is called the bulb. Second: a modified form of Wheatstone bridge, which measures the change in resistance with change of temperature and consequently indicates the change of temperature. The box in Fig. 66 holds a galvanometer and a bridge combined. The dial is in the rheostat arm

of the bridge. The resistance is so adjusted that the dial reads direct in degrees for a given range of temperature.

The resistance of the bulb changes with the temperature approximately according to the law stated on p. 78,

$$R_t = R_o(1 + at),$$

where a is a coefficient which depends upon the nature of the metal used, but which is fairly constant over wide ranges of temperature for the alloys and metals used.

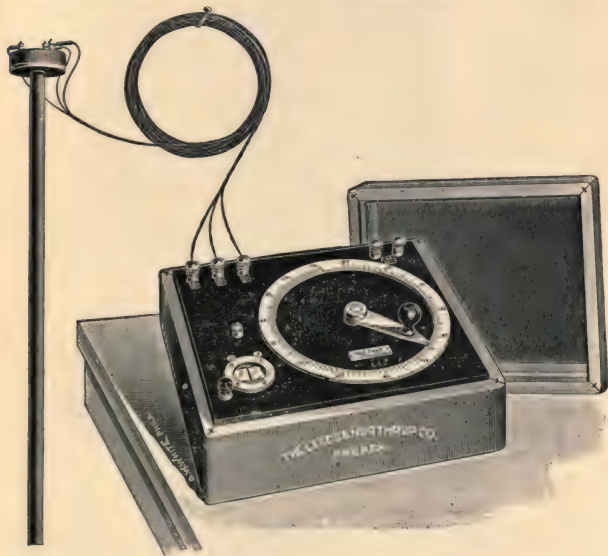


FIG. 66.—Resistance Pyrometer.

The real purpose, or function, of the Wheatstone bridge is to get the resistance of the bulb. From this resistance the change in temperature may be obtained from the above formula.

The bridge may be made to read the change in resistance directly by placing in series with the rheostat arm a resistance equal to that of the bulb at the lowest temperature for which the instrument is to be used. Any increase in temperature above the lowest, or standard, in temperature produces an increase in resistance. The

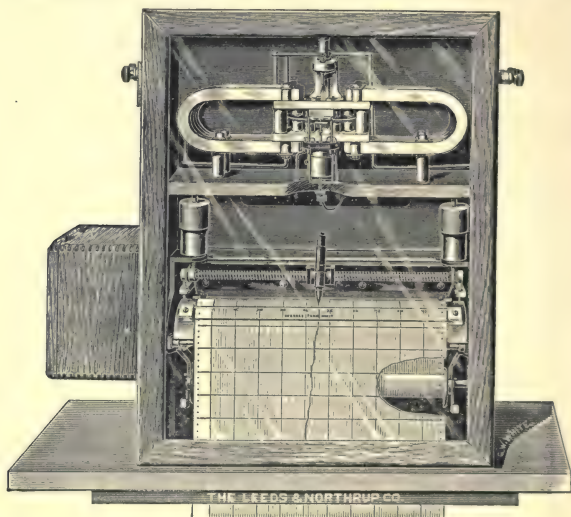


FIG. 67.—Recording Resistance Pyrometer.

electrical circuit may be so arranged that no current will flow when the rheostat arm is adjusted so as to have the same amount of resistance as was added to the bulb because of the rise in temperature of the bulb. If, instead of marking the resistances on the rheostat arm, the increase in temperature which produces the resistance is marked, the pyrometer becomes direct reading.

A potentiometer may be used with the fire end, or bulb, in place of the balance indicator. With the potentiometer the change in resistance may be measured with greater accuracy and consequently the temperature may be determined more accurately.

97. The Bolometer. The bolometer is in reality a delicate type of resistance pyrometer. Two resistance members are constructed exactly alike, each being made of ten or more strips of blackened platinum foil, 1 cm. long, 5 mm. wide, and .002 mm. thick. One set is arranged to be exposed to radiated rays if desired, and is placed in the unknown arm of the Wheatstone bridge. The duplicate set is placed in series with the rheostat arm and is always protected from the radiated rays which are being investigated. The bridge enables the investigators to obtain the change in resistance.

If radiated rays be allowed to fall upon the blackened platinum they will be absorbed and will tend to increase the temperature and consequently the resistance of the platinum foil. This effect is rapid since the weight of the foil is so small that the heat capacity of the foil is extremely minute. Less than .00000001 calorie has been sufficient to give an appreciable reading.

It is by this instrument that the distribution of heat energy in the spectrum may be investigated.

98. Thermo-junction Pyrometers. The Bristol pyrometer is a good sample of commercial instruments of the thermo-junction type. It has two fire ends, one encased in an iron tube, for temperatures up to 2000° F., and a second encased in a quartz tube for temperatures up to 2200° F.

The fire ends consist simply of two heavy wires of different alloys, welded together at the ends but otherwise insulated by an asbestos cover. The other ends of these two wires are connected through suitable leads to a millivoltmeter. This instrument has a double scale, and a double set of connections and reads directly in degrees F. on either scale.

The action of the instrument is dependent upon a very peculiar electrical effect of which temperature measurement is the most important practical application. To produce

this effect, two wires of any two different metals or alloys, such as one platinum and one platinum-iridium wire, are welded together. The other ends are connected to a millivoltmeter or galvanometer. Upon the application of heat to the welded point or junction a difference in E.M.F. is set up and consequently an electric current will flow through the electric circuit. The amount of electrical pressure (E.M.F.) is usually in proportion to the difference in temperature between the ends at the junction and the other two ends of the wires forming the junction.

The Bristol pyrometer is often equipped with a mercury compensator which reduces the resistance of the circuit with rise of temperature of the cold ends so that no corrections need to be made in the scale readings. The

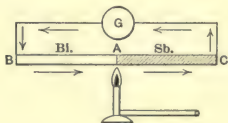


FIG. 68.

readings of a thermo-couple indicate differences in temperature and not definite temperatures, except as a bath may be used to keep the ends of the couple which are connected to the instrument at the temperature for which the instrument was calibrated. By the use of a compensator this difference is always indicated in reference to a standard temperature. Thus the scale may be made to read temperatures directly.

For high temperatures it is necessary to select metals or alloys which will not oxidize or melt. This requirement limits the use of the thermo-junction pyrometer to temperatures below 2500° F. For measurements by scientists of temperatures above the melting-point of steel, the couple has usually been made up of platinum and a platinum alloy.

The alloy contains either 10 per cent of iridium or 10 per cent of rhodium and 90 per cent platinum. In the Bristol pyrometer various alloys are used, but the preferred combination for instruments used in tempering steel and for other high temperature purposes is tungsten steel and pure nickel. The steel is positive and may contain from 5 to 25 per cent of tungsten. The nickel is negative and may be alloyed with German silver.

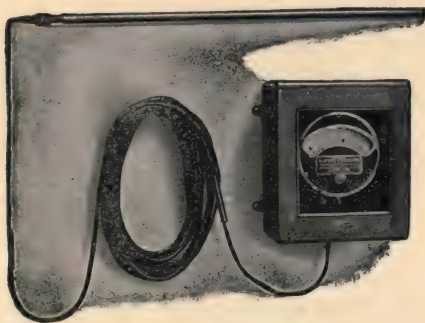


FIG. 69.

Uniformity of effect is usually the basis of selection of the thermo-junction for low temperatures. Because of the small heat capacity of these junctions they are especially valuable for use at extremely low temperatures such as that of liquid hydrogen.

A millivoltmeter is used to register the thermo-electric E.M.F. produced by the junction. If the effect is in direct proportion to the E.M.F., the difference in temperatures corresponding to linear unit deflection may be marked on the scale of the instrument. By the use of a compensator or a mercury bath, these temperature differences become direct readings in reference to a standard temperature.

A potentiometer, which is an instrument for determining E.M.F., may be used with a thermo-junction when greater accuracy is desired than can be obtained with a millivoltmeter.

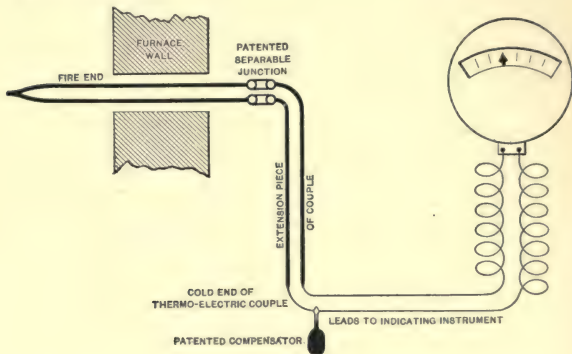


FIG. 70.

99. Heat Radiation Pyrometers. A radiation pyrometer may be constructed by connecting a large number of thermo-junctions in series and connecting these to a galvanometer. The large number of junctions is called a thermopile and multiplies the effect of a single couple or junction. For a given change in temperature the E.M.F. of a thermopile equals the E.M.F. of one junction times the number of junctions.

One or more of these junctions may be mounted upon the same suspension which supports the moving coil of the galvanometer and



FIG. 71.

be connected to the moving coil. In this way the parts may be made extremely light, and small quantities of energy may be made to produce

an appreciable deflection. Radiations are allowed to enter and fall upon the junction only. Thus the junction is the only part which is heated.

100. Optical Pyrometers. Nearly all of the so-called optical thermometers compare the intensity of the radiation from a part of the spectrum, such as, for instance, the red rays, with the intensity of illumination from a standard source. In other words, they all compare the intensity of definite wave lengths. A photometer is usually used for the comparison. Optical pyrometers are necessarily fragile and require delicate adjustments and a large amount of skill and judgment in their use. Consequently, they are not adapted for shop work in the hands of workmen.

101. Fuel Calorimeters. The problem of obtaining the heat value of fuels has many difficulties. To measure the heat produced it is necessary to burn a small sample under conditions that will produce *complete combustion* and will enable the investigator to *measure all of the heat* given up during the burning.

To produce *complete* combustion in large quantities of coal is difficult under the most favorable condition. There is usually considerable unburned carbon in the ash and clinker. To completely burn a sample of coal or oil weighing *one gram* and to measure the heat accurately is very much more difficult. All blasts which would tend to blow about the finely divided particles of fuel as sparks must be avoided. A high temperature must be maintained both in the sample and in the flame, because *complete oxidation takes place only at high temperatures*. If the sample is allowed to cool, the combustion will not be complete. If the flame comes in contact with a cold wall, combustion will not be complete.

Everyone knows that a single large lump of coal removed from the fire while white hot soon cools and stops burning. A small quantity of powdered coal will cool almost as quickly if exposed in a similar way. On the other hand, if a live coal is held in oxygen gas it will be seen to burn brilliantly. This gives us a clue to the two methods which are in use in commercial determinations of the fuel value of a coal.

First Method. In Fig. 72 is shown a so-called Mahler bomb calorimeter. It is selected as a typical illustration chiefly because the Mahler design was the first moderately expensive design which came into common use and because it is still in use. It gets its name from the heavy walled "bomb," *B*, in which the fuel is burned. It will be noticed that the walls of this steel bomb are thick and that it is provided with a cover which may be screwed on tightly with a wrench while the bomb is held in the vise, *V*. The

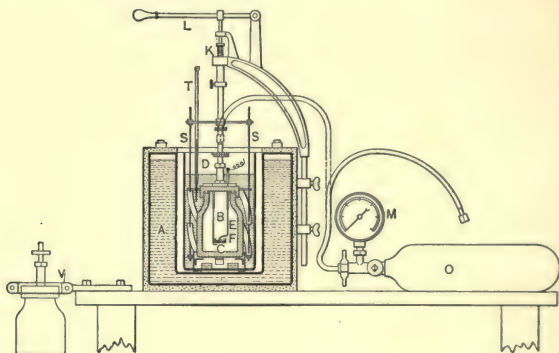


FIG. 72.—Mahler Bomb Calorimeter.

weighed sample of coal is placed in the crucible, *C*. A wire, *F*, is connected to the rod, *E*. This in turn passes through an insulating bushing and makes possible an electrical connection to the outside. The other end of *F* makes contact with the crucible, if it is nickel or platinum, and thus the circuit connection is made to the metal rod holding the crucible and to the bomb itself. To pass a current through the platinum coil, *F*, it is necessary to connect one wire from a source of electrical energy to the rod, *E*, and a

second wire directly to the bomb itself. When a current flows, the coil, *F*, can be heated by it to redness. The red-hot platinum wire is relied upon to cause the fuel to ignite.

To make a determination, one gram of coal is placed in the crucible, a cover (not shown), is put on, and the wire, *F*, is adjusted. A known weight of water is placed in the calorimeter and the bomb is immersed in it. Oxygen is admitted from the tank, *O*, until the gauge pressure is about 250 or 260 lbs. and then the valve is closed. The stirrer, *S*, which carries a set of vanes, is made to rotate by moving the screw, *K*, up and down by means of the lever, *L*. The temperature of the water is taken with the thermometer, *T*, and the electric circuit is at once closed to ignite the coal, *S*. The thermometer is read at regular intervals until several minutes after it has ceased to rise.

From the rise in temperature, the weight of water plus the water equivalent of the calorimeter and bomb, and the weight of coal, the energy per pound may be computed. The value will be what is often called the *higher value*. That is, it will be the value which results from cooling all of the products of combustion to the temperature of the apparatus. To do this will result in the condensation of all of the H_2O produced in the form of steam during the combustion of any constituents of the coal containing hydrogen. The value which does not include the latent heat of vaporization of this condensed water is called the *lower value*.

This apparatus, like all bomb calorimeters, requires a great deal of skill for successful operation. Because of the high pressures necessary, the bomb must be provided with some sort of lead gasket or packing, and this wears out very quickly.

The interior of the bomb is usually plated with platinum, gold, nickel, or enamel to prevent oxidization. None of these coatings is durable indefinitely, although platinum, with careful use, will last a long time.

A considerable supply of oxygen must be available if a number of determinations are to be made. It is estimated that the present minimum cost of oxygen for the determination of the fuel value of 1 gram of coal in an oxygen bomb is 10 cents.

Second Method. There are many makers of bomb calorimeters using oxygen, but each bomb operates in practically the same way as the Mahler bomb and differs only in details of mechanical construction. It is possible to avoid the use of oxygen, however, by using in its place a chemical compound containing oxygen. Thus, if with one gram of coal there is mixed 3.25 grams of potassium nitrate and 9.75 grams of potassium chlorate, complete combustion may be obtained without an external supply of oxygen. This mixture might be placed in the crucible, *C*, of Fig. 72 and ignited as in the Mahler bomb. However, it is usual, whenever this method is followed, to use a much more simplified form of apparatus, which allows the gaseous products to bubble up through water and then escape. Results obtained tend to be too high because of the heat given off in breaking down the potassium chlorate, and they tend to be too low because of incomplete combustion.

In Fig. 73 is shown a section through a Bahrdrf calorimeter and an enlarged view of some of the parts. The crucible, *C*, is used to contain the gram sample of coal. The oxygen is supplied for burning this through the pipe, *EA*, from a cylinder outside of the apparatus. Then the stopper at *D* supporting the crucible, *C*, is placed in the chamber, *P*, in the left-hand figure. This chamber is surrounded by a weighed quantity of water and the water equivalent of the apparatus is determined as in previous experiments. The fuel may be ignited by first placing sulphur on top of it and igniting the sulphur with a hot rod before placing the crucible in the chamber or it may be ignited electrically, as in the Mahler bomb. The products of combustion

escape through the spiral copper tubing at the opening, *S*, after being thoroughly cooled by the water. The results obtained in this way are not as satisfactory as may be obtained from a bomb calorimeter, but the apparatus has the advantage of being extremely cheap in first cost and will give a rough comparative test. Liquids may be tested in the same apparatus by replacing the crucible, *C*, and the stopper at *D* with a lamp, *G*, placed in a holder, *R*, which is carried by the stopper, *K*. The weighed amount of fuel is placed in the lamp, *G*, and the wick is ignited

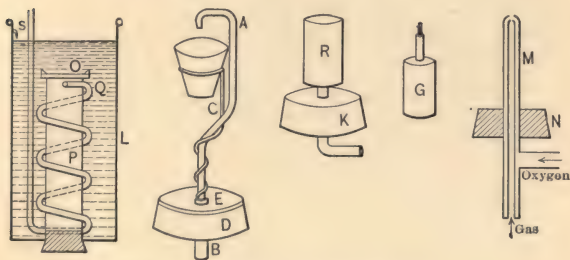


FIG. 73.—Bahrdrf Calorimeter Parts.

and the lamp quickly placed inside the calorimeter. The flame is watched through a glass plate, *O*, in the top of the chamber, *P*, of the left-hand figure. The fuel value of any distillate which does not leave a tarry residue may be determined in this way. The fuel value of a gas may be obtained by inserting into the chamber, *P*, the gas burner, *M*, which extends through the cork, *N*. To use this apparatus for gas, requires a gas meter to measure the volume of the gas. It is necessary to make a correction in the readings of the meter for the change of volume from that under standard conditions due to the temperature and the pressure of the room.

102. Indicators. Before studying how the Watts indicator enables us to compute the I.H.P. of an engine let us review the computation for a double-acting steam engine. (See pages 141 and 151.)

Let P_{H_1} = average pressure of steam admitted to head end;

P_{C_1} = average pressure of steam admitted to crank end;

P_{H_2} = average back pressure of steam rejected from head end;

P_{C_2} = average back pressure of steam rejected from crank end;

L = common length of both strokes. Then

- (1) $(P_{H_1} - P_{C_2}) = \text{M.E.P. for the forward stroke.}$
- (2) $L(P_{H_1} - P_{C_2}) = \text{work done in the forward stroke.}$
- (3) $L(P_{C_1} - P_{H_2}) = \text{work done in the return stroke.}$
- (4) $LP_{H_1} - LP_{C_2} + LP_{C_1} - LP_{H_2} = \text{work done in the two strokes.}$

Let us consider combining these terms as follows:

- (5) $P_{H_1} - P_{H_2} = \text{M.E.P. of the medium in the head end.}$
- (6) $L(P_{H_1} - P_{H_2}) = \text{work left in head end by the medium.}$
- (7) $L(P_{C_1} - P_{C_2}) = \text{work left in crank end by the medium.}$

The sum of 7 and 6 is algebraically equal to 4 and it therefore follows that a computation in which the M.E.P. of the medium is used will give the same result as would be obtained by using the M.E.P. for the stroke.

The purpose of the indicator diagram is to enable the steam engineer to experimentally find the mean effective pressure of the medium during the actual stroke of any engine or compressor. Whatever the special feature or design added by the maker, the indicator must consist primarily of a small cylinder containing a piston which

moves and transmits its linear motion to a pencil. This small cylinder connects directly with the main cylinder; under test, therefore, the little piston is made to move by the same force which moves the big piston. The piston acts against a spring and the whole device must be so adjusted that the motion of the pencil is in proportion to the gauge pressure of the steam. The range of the instrument is usually varied by changing the spring. Springs are

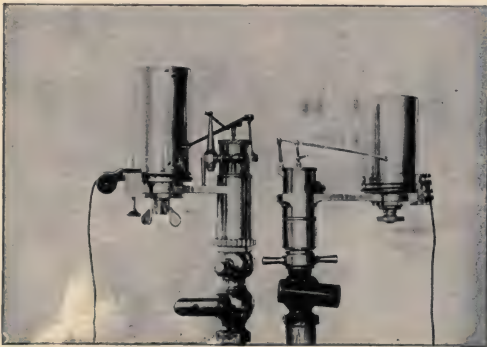


FIG. 74.—Thompson & Crosby Indicator.

calibrated in terms of the pressure in pounds per square inch gauge required on the piston to produce one inch motion of the pencil and usually bear this number stamped upon them.

Crosby springs are designed to compress an amount equivalent to an upward motion of $1\frac{3}{4}$ inches and they act under tension for pressures less than atmospheric.

All makes of steam indicators have a rotating drum which carries a paper "card." Upon this card when the drum is at rest the pencil may be made to trace a vertical line by the motion of the indicator piston caused by the pressure in the engine cylinder.

If the lower side of the piston is connected to the atmosphere the piston will have equal pressures on both sides. If the drum is rotated it will then trace a horizontal line which shows the atmospheric pressure. If the drum is connected through suitable cords and levers to the cross-

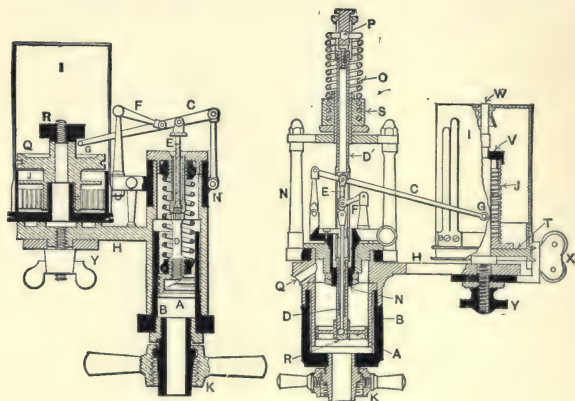


FIG. 75.—Section of Indicators.

head of the engine it may be made to move with the piston in the cylinder of the engine.

When the piston of the indicator is connected to one end of the steam cylinder and the drum is rotated from the cross-head, these motions are combined and a figure is traced on the paper like that shown in Fig. 56. The height above the atmospheric line at any point indicates, in spring units, the pressure on the piston at the corresponding point in the stroke. By determining the average height above the atmospheric line, the M.E.P. (mean effective pressure) for the medium may be obtained.

If a three-way cock is used in piping the indicator to the ends of a cylinder, a diagram like that shown in Fig. 56

may be obtained by connecting the piston to first one end and then the other. From this the M.E.P. for each end of the cylinder may be obtained. By substituting in the formulæ in Chapter VI, page 150, the I.H.P. (indicated horsepower) may be obtained.

103. Steam Calorimeters. To determine the quantity of heat energy in a given weight of steam, it is customary to use one of two kinds of calorimeters; either the throttling calorimeter or the separating calorimeter.

The Throttling Calorimeter. Where the quantity of the minute drops of entrained moisture is small, the throttling calorimeter furnishes the most accurate means of finding out the per cent of moisture and the "quality" of the steam. Fig. 76 shows a steam calorimeter of the throttling type made from pipe fittings. This consists essentially of a sampling tube extending into the steam main with holes arranged regularly according to some scheme which gives a fair sample of the steam passing through the main. Engineers are not agreed as to the best method of obtaining such a sample. The journal of the A.S.M.E., for November, 1912, page 1836 and context, gives a description of the calorimeter recommended by the 1912 code.

The steam passes the thermometer *A* at the temperature and pressure of the steam main. It next passes through a $\frac{1}{8}$ -inch hole in a small disk in the piping. Here it expands to atmospheric pressure without any loss of heat energy. The thermometer *B* reads its new temperature. It may not be clear to the student at first that the temperature of the steam should be different when it reaches thermometer *B* from that at *A*, but if the student will notice in the steam table the temperature of saturated steam under high pressure such as 165 lbs. will be 373.2°. At atmospheric pressure the temperature of saturated steam is 212°. Now, if the steam in the steam main is dry and saturated it will contain 1196.1 B.T.U. of heat energy. After passing through the hole in the disk it would still contain this 1196.1 B.T.U.

The total heat of dry saturated steam at 14.7 lbs. pressure is 1150.1 B.T.U. The difference between these two total heats or 46 B.T.U. would therefore be left in the steam and would superheat it. The amount of superheat would be 46 divided by .48, the specific heat of steam, or 98°.

If, on the other hand, this steam had contained 2 per cent of moisture at 160 lbs. pressure, there would have been 2 per cent of the water which would not have had any latent heat in it, but only the sensible heat necessary to raise it

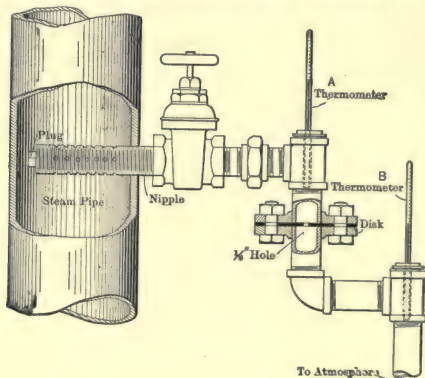


FIG. 76.—Throttling Calorimeter.

to the temperature of the steam at this pressure, 273.2°. This 2 per cent of water did not receive latent heat energy to the amount of $.02 \times 850.9$, or 17.02 B.T.U. The total heat of the steam containing 2 per cent of moisture was, therefore, 1179.1 B.T.U. When this steam was expanded at the disk to atmospheric pressure, it accordingly had only 29.0 B.T.U. in it which caused superheating. The temperature therefore which was read by thermometer *B* was 29.0 divided by .48, or 60.4.

By allowing steam of unknown quality from a main to

blow through the calorimeter and by taking the reading of the thermometer, the problem given above may be worked backwards to determine the quality.

The Separating Calorimeter. The separating calorimeter is a device intended to mechanically extract the entrained moisture from the steam. Thus it is intended to take out all of the small drops of water and deliver dry saturated steam.

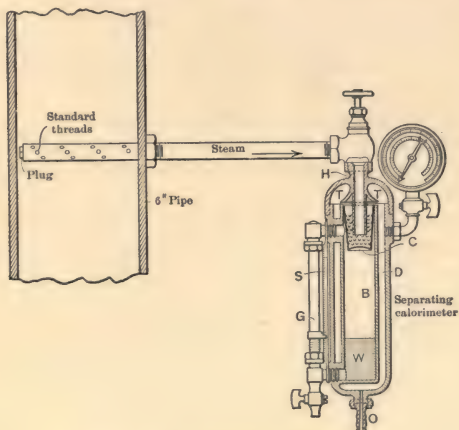


FIG. 77.—Separating Calorimeter.

The inverted cup *C* is surrounded with gauze or other perforated material. The steam enters the area above the cup and then passes out through the small spaces into the central space *B*. The object of the gauze or fine perforation is to provide a surface upon which the moisture may collect and from which it falls in large drops to the bottom, *W*. The dry steam rises through *T, T*, and then passes down through the orifice, *O*.

The water in *W* rises and its amount may be directly

read upon the scale, S , by observing its height in the gauge glass, G . The water may also be weighed by drawing it off through the cock at the bottom of G .

The weight of dry saturated steam passing through the orifice may be computed from the following formula, which is frequently used.

$$\text{The quality of the steam} = \frac{W_1}{W_1 + W_2}$$

when W_1 = weight of the steam passing through the orifice, O , and W_2 = the weight of water collected in W . From the quality, the total heat of the steam may be readily obtained from the steam tables.

The separating calorimeter is not so reliable as the throttling calorimeter. Therefore, where the quantity of moisture in the steam is small, the throttling calorimeter is generally used.

Sometimes a throttling calorimeter is connected to O on the separating calorimeter. In this way steam having any per cent of moisture may be accurately tested for moisture.

Other Calorimeters. Various schemes have been used to combine the effects obtained in the throttling and in the separating calorimeters. The student should have no trouble in understanding them, however, if he has followed the description given above and understands the throttling calorimeter.

The value of the total heat of steam may be obtained by condensing it in a barrel of cold water of known weight and obtaining the rise of temperature and the gain in weight of the water. A continuous-flow condenser may also be used. This consists essentially of the same parts as the large condenser shown on page 168. The temperature of water is measured as it enters and leaves. The circulating water and the condensed water is weighed. No pump is necessary and the apparatus may be rather small.

The computation is similar to those already made for the condenser.

APPENDIX A

TABLE 1

USEFUL NUMBERS

$$\begin{aligned}\pi &= 3.1416 = \frac{22}{7} = \frac{\text{circumference}}{\text{diameter}}. & \text{Surface of cyl.} &= 2\pi rl + 2\pi r^2. \\ \pi^2 &= 9.8696; \quad \frac{1}{\pi} = .3183 = \frac{7}{22}. & \text{Volume of cyl.} &= \pi r^2 l. \\ \text{Area of circle} &= \pi r^2 = \frac{\pi d^2}{4} = .7854 d^2 = \frac{11}{14} d^2. & \text{Surface of sphere} &= 4\pi r^2. \\ & & \text{Volume of sphere} &= \frac{\pi d^3}{6} = \frac{4\pi r^3}{3}.\end{aligned}$$

METRIC-ENGLISH EQUIVALENTS

1 cm.	= .39 in.	1 in.	= 2.54 cms.
1 m.	= 39.37 ins.	1 ft.	= 30.48 cms.
1 m.	= 3.28 ft.	1 ft.	= .305 m.
1 km.	= .6 mi.	1 mi.	= 1.609 km.
1 gm.	= .035 oz. (avoir.)	1 oz.	= 28.35 gms.
1 kgm.	= 2.204 lbs. (avoir.)	1 lb.	= 453.6 gms.
1 sq.cm.	= .155 sq.in.	1 sq.in.	= 6.45 sq.cms.
1 cu.cm.	= .061 cu.in.	1 cu.in.	= 16.39 cu.cms.
1 litre	= .2642 gal. U.S.	1 gal. U.S.	= 3.785 litres.
1 litre	= .2200 gal. British	1 gal. British	= 4.546 litres

UNITS OF FORCE, WORK, POWER, ETC.

$$\begin{aligned}1 \text{ dyne} &= .00102 \text{ gm.} \\ 1 \text{ ft.-lb.} &= 1.356 \times 10^7 \text{ ergs.} \\ 1 \text{ joule} &= 10^7 \text{ ergs.} \\ 1 \text{ watt} &= 10^7 \text{ ergs/sec.} = 1 \text{ joule/sec.}\end{aligned}$$

MECHANICAL EQUIVALENTS OF HEAT

$$\begin{aligned}1 \text{ gm. of water heated } 1^\circ \text{ C.} &= 4.2 \times 10^7 \text{ ergs.} \\ 1 \text{ lb. of water heated } 1^\circ \text{ C.} &= 1400 \text{ ft.-lbs.} \\ 1 \text{ lb. of water heated } 1^\circ \text{ F.} &= 780 \text{ ft.-lbs.} \\ 780 \text{ ft.-lbs.} &= 1 \text{ B.T.U.} \\ 4.2 \times 10^7 \text{ gms.} &= 1 \text{ calorie (= 4.2 joules).} \\ 4.28 \times 10^4 \text{ gr.cms.} &= 1 \text{ calorie (= 4.2 joules).} \\ 4.2 \text{ watt-seconds} &= 1 \text{ calorie (= 4.2 joules).}\end{aligned}$$

(For a complete table showing the relation between the various units see Table II.)

TABLE II
EQUIVALENT VALUES OF ELECTRICAL, MECHANICAL, AND HEAT-UNITS
From Kent's "Mechanical Engineers' Pocket-Book"

WORK UNITS.			POWER UNITS.			HEAT-UNITS, WORK.		
Unit.	Equivalent Value in Other Units		Unit.	Equivalent Value in Other Units		Unit.	Equivalent Value in Other Units.	
K.W. Hour = 1 Kilo- Hour =	1,000 watt hours.			1,000 watts.		1 Heat-Unit	1 British Thermal Unit.	
	1.34 H.P. hours.			1.34 horse-power.		=	Symbol, B.T.U.	252 calories.
	2,654,200 ft.-lbs.			2,654,200 ft.-lbs. per hour.				
	3,600,000 joules.			44,240 ft.-lbs. per minute.				
	3,412 heat-units (B.T.U's.).			737.3 ft.-lbs. per second.				
H.P. Hour = 1 H.P. Hour =	367,000 kilogram-meters.		1 Kilo- Watt =	3,412 heat-units per hour.		1 Heat- Unit.	1,055 watt seconds.	
	.235 lb. carbon oxidized with perfect efficiency.			56.9 heat-units per minute.		=	780 ft.-lbs.	
	3.52 lbs. water evap. from and at 212° F.			.948 heat-unit per second.			107.6 kilogram-meters.	
	22.75 lbs. of water raised from 62° to 212° F.			.253 lb. carbon oxidized per hr.			.000293 K.W. hour.	
	746 K.W. hour.			3.52 lbs. water evap. per hour from and at 212° F.		B.T.U. =	.000393 H.-P. hour.	
1 Joule = 1 Joule =	1,980,000 ft.-lbs.			746 watts.			.000688 lb. carbon oxidized.	
	2,545 heat-units (B.T.U's.).			.746 K.W.			.001036 lb. water evap. from and at 212° F.	
	273,740 kg.m.			33,000 ft.-lbs. per minute.		1 lb. carbon oxidized	14,544 heat-units.	
	.175 lb. carbon oxidized with perfect efficiency.			550 ft.-lbs. per second.			1.11 lb. anthracite coal oxidized.	
	2.64 lbs. water evap. from and at 212° F.		H.-P. =	2,545 heat-units per hour.			2.5 lbs. dry wood oxidized.	
1 Ft.-lb. = 1 Ft.-lb. =	17.0 lbs. water raised from 62° F. to 212° F.			42.4 heat-units per minute.			21 cu.ft. illuminating gas.	
	1 watt second.			.707 heat-unit per second.			5.71 H.-P. hours.	
	.00000278 K.W. hour.			.175 lb. carbon oxidized per hr.			11,315,000 ft.-lbs.	
	.009477 heat-units (B.T.U's.).			2.64 lbs. of water evap. per hour from and at 212° F.			15 lbs. of water evap. from and at 212° F.	
	.7373 ft.-lb.		1 Watt =	1 joule per second.				
1 Kilo-gram meter = 1 Kilo-gram meter =	1.356 joules.			.00134 H.-P.		1 lb. water evap. from 212° F. =	283 K.W. hour.	
	.1383 kg.m.			3,412 heat-units per hour.			.379 H.-P. hour.	
	.00000377 K.W. hour.			.7373 ft.-lb. per second.			970 heat-units.	
	.001285 heat-unit (B.T.U.).			.0035 lb. water evap. per hour from and at 212° F.			103,900 kg.m.	
	.0000005 H.-P. hour.			44.24 ft.-lbs. per minute.			1,019,000 joules.	
1 Kilo-gram meter = 1 Kilo-gram meter =	7,233 ft.-lbs.			1 lb. pull at half a mile per hour (approx.).			751,300 ft.-lbs.	
	.00000365 H.-P. hour.			8.19 heat-units per sq.ft. per minute.			.0664 lb. of carbon oxidized.	
	.00000272 K.W. hour.			6,371 ft.-lbs. per sq.ft. per minute.				
	.00993 heat-unit (B.T.U.).			.193 H.-P. per sq.ft.				
			HEAT UNITS, POWER.					
			1 Kilo-gram meter =	.122 watt per sq.in.		1 Heat-Unit per sq.ft. per min. =	.0176 K.W. per sq.in.	
				.0236 H.-P. per sq.ft.			.0236 H.-P. per sq.ft.	

TABLE III
HEAT ENERGY DEVELOPED BY OXIDATION
 (Assume that the products are gaseous)

GASES.	B.T.U.		Calories.	
	Per. Lb.	PerCu.ft.	Per Gm.	Per Liter.
Acetylene.....	21,400	.....	11,930	
Carbon vapor.....	20,400	13,600	11,300	12,143
Carbon monoxide to CO ₂	4,340	338	2,410	3,040
Coal gas.....	.....	680	.....	6,100
Ethane.....	22,200	1,865	12,350	16,700
Ethylene.....	21,400	1,677	11,900	14,900
Hydrogen.....	62,030	348	34,460	3,090
Illuminants (average).....	.....	2,000	.....	.....
Methane (CH ₄).....	23,560	1,052	.....	.....
Nitrogen to N ₂ O.....	.....	.....	654	.....
“ NO.....	.....	.....	1,541	.....
“ N ₂ O ₅.....	.....	.....	143	.....
Pittsburgh natural.....	.....	891	.....	8,050
Producer (Siemens).....	.....	200	.....	1,800
Water gas (best).....	.....	347	.....	3,100
LIQUIDS.				
Alcohol, ethyl.....	12,900	.....	7,180	.....
“ methyl.....	9,540	.....	5,310	.....
“ denatured, +8% H ₂ O... ..	11,500	.....	6,450	.....
Benzine.....	17,900	.....	9,980	.....
Carbon disulphide.....	5,820	.....	3,244	.....
Crude oil, sp.gr. .886.....	20,700	.....	11,500	.....
Dynamite, 75%.....	.....	.....	1,290	.....
Fuel oils, sp.gr. .965.....	18,600	.....	10,300	.....
Gasoline, sp.gr. .720.....	20,300	.....	11,300	.....
Kerosene, sp.gr. .795.....	20,000	.....	11,000	.....
Olive oil.....	.....	.....	9,400	.....
Petroleum ether, sp.gr. .689.....	22,000	.....	12,200	.....
SOLIDS.				
Aluminium.....	.....	.....	7,140	.....
Carbon burned to CO.....	4,330	.....	2,410	.....
“ CO ₂	14,460	.....	8,030	.....
Copper burned to Cu ₂ O.....	.....	.....	321	.....
“ CuO.....	.....	.....	590	.....
Gunpowder.....	.....	.....	730	.....
Iron burned to FeO.....	.....	.....	1,350	.....
Lard.....	.....	.....	9,200	.....
Lead.....	.....	.....	243	.....
Magnesium.....	.....	.....	6,080	.....
Manganese.....	.....	.....	1,720	.....
Naphthalene, C ₁₀ H ₈.....	.....	.....	14,544	.....
Sulphur.....	.....	.....	2,240	.....
Tin.....	.....	.....	575	.....
Zinc.....	.....	.....	1,200	.....
Wood, pine + 12.2% H ₂ O.....	.....	.....	4,420	.....
“ oak + 13.3% H ₂ O.....	.....	.....	4,000	.....

TABLE IV*
ANALYSIS OF VARIOUS COALS (IN PER CENT)

Sample No.	Moisture.	Volatile Matter.	Fixed Carbon.	Ash.	Sulphur.	Hydrogen.	Carbon.	Nitrogen.	Oxygen.	Calories per Gramme.
1	2.63	33.00	50.96	13.41	.94	4.87	70.73	1.38	8.67	....
2	3.36	32.88	51.33	12.43	1.01	4.84	68.69	1.54	11.49	....
3	3.24	17.46	66.69	12.61	1.24	4.15	74.09	1.44	6.47	....
4	2.23	16.02	72.55	9.20	1.87	4.24	78.83	1.38	4.48	....
5	2.19	19.47	66.71	11.63	1.28	4.17	75.31	1.53	6.08	....
6	38.81	25.48	27.29	8.42	.97	7.09	37.45	.50	45.57	3526
7	33.38	27.44	29.62	9.56	.94	6.77	41.31	.67	40.75	3994
8	22.71	34.78	36.60	5.91	.29	6.14	52.54	1.03	34.09	5115
9	15.54	33.03	46.06	5.37	.58	5.89	60.08	1.05	27.03	5865
10	11.44	33.93	43.92	10.71	4.94	5.39	60.06	1.02	17.88	6088
11	3.42	34.36	58.83	3.39	.58	5.25	77.98	1.29	11.51	7852
12	2.7	14.5	75.5	7.3	.99	4.58	80.65	1.82	4.66	7845
13	3.26	14.57	78.20	3.97	.54	4.76	84.62	1.02	5.09	8166
14	2.07	9.81	78.82	9.30	1.74	3.62	80.28	1.47	3.59	7612
15	2.76	2.48	82.07	12.69	.54	2.23	79.22	.68	4.64	6987
16	3.33	3.27	84.28	9.12	.60	3.08	81.35	.79	5.06	7417

* From U. S. G. S. Prof. Paper 48. Pages 196-200, Smithsonian Physical Tables.

TABLE V
GAS ANALYSES (BY VOLUME IN PER CENT)

No.	CO ₂	O ₂	CO	H ₂	CH ₄	N	C ₂ H ₄	H ₂ S	Illum.
1	9.0	0.2	11.2	6.0	8.9	64.7			
2	.26	.42	.73	1.86	93.0	3.02	.47	.15	
3	.80	1.8	3.5	20.02	72.18	8.9	.....	.....	6.30
4	1.16	.....	6.16	50.59	34.80	2.06	.....	.....	5.23
5	1.50	.50	6.30	50.10	33.10	2.70	.....	.....	5.80
6	.84	.25	4.62	43.95	39.33	4.79	.....	.....	6.22
7	6.02	.....	30.28	49.68	3.46	10.22	.....	.....	0.34
8	6.10	.....	22.23	28.7	1.00	41.9	.....	.....	.....
9	12.9	.....	13.2	24.8	2.3	46.8	.....	.....	.....
10	17.4	1.0	1.0	.....	.....	80.6	.....	.....	.....
11	10.8	8.4	.30	.....	.....	80.8	.....	.....	.....

NOTE. 1. Producer Gas, U. S. G. S. Prof. Paper 48, Part III, p. 1136; 2. Natural Gas, E. and M. Journal; 3. Pittsburgh Natural Gas, Poole; 4. Newton, Mass., Coal Gas from Poole (Thwaite); 5, 6. Paris, France, Coal Gas from Poole (Thwaite); 7. Bridgeport, Conn., Water Gas, from Poole; 8. Producer Gas, Siemens; 9. Producer Gas, Mond's; 9, 10. Flue Gas, B. of M. Bul. 2, p. 37.

TABLE VI
SPECIFIC HEAT TABLE

Substance.	Solid.		Liquid.		Gas.		
	Range in Temp. Deg. C. From To	Spec. Heat.	Range in Temp. Deg. C. From To	Spec. Heat.	Range in Temp. Deg. C. From To	Const. P.	Const. V.
Air.....	.....	....	....	....	10, 100	.238	.169
Alcohol, ethyl.....	.....	....	30	.615			
" methyl.....	.....	....	5-10	.590			
Aluminium.....	15, 97	.212					
Ammonia.....	.....	....	0	1.012	10, 100	.508	.391
Antimony.....	13, 106	.0486					
Arsenic, crys alline.....	.....	.083					
" amorphous.....	.....	.076					
Bismuth.....	9, 102	.0298					
Brass, average.....	15, 100	.094					
Bromine.....	.....	.084		.107		.055	
Benzine.....	.....	....	19, 38	.416			
Carbon, charcoal.....	8, 98	.242					
" gas coal.....	8, 98	.204					
" diamond.....	8, 98	.105					
Carbon dioxide (CO ₂) ..	.....	....	....	....		.216	.168
Carbon monoxide (CO) ..	.....	....	....	....		.242	.173
Chloroform.....	.....	....	at 30	.235	100, 120	.147	
Copper.....	15, 100	.0933					
Ether, sulphuric.....	.....	....	at 0	.529	70, 200	.487	
Glass.....	15, 97	.12					
".....	.....	.20					
Hydrogen.....	.....	....	....	....		3.41	2.81
Iron, cast.....	.....	.12					
" wrought.....	.....	.11					
India-rubber.....	.....	.20					
Lead.....	.....	.0315		.0402			
Mercury.....	-70, -40	.0319	17, 48	.0335			
Nickel.....	14, 97	.1092					
".....	100	.113					
Nitrogen.....	.....	....	....	....		.244	.173
Oxygen.....	.....	....	....	....		.217	.155
Petroleum.....	.....	....	....	.460			
Platinum.....	.....	.0323					
Silver.....	.....	.0559					
Steel.....	.....	.117					
Sulphur.....	0-52	.180					
Sulphuric acid.....	.....	....	16, 20	.332			
" +5H ₂ O.....	.....	....	16, 20	.576			
Tin.....	.....	.056					
Tantalum.....	-185, +20	.033					
Tungsten.....	0, 100	.034					
Turpentine.....	.....	....	40	.459			
Zinc.....	0, 100	.0935					
".....	100	.095					
".....	200	.100					
".....	300	.104					
Water.....	-20, 0	.504	20	1.000	100, 200	.480	

TABLE VII
COEFFICIENTS OF EXPANSION, CENTIGRADE

Substance.	Linear.* × 10 ⁴	Substance.	Cubical.† × 10 ³
SOLIDS			
Aluminium	.2313	Antimony	.3167
Brass { Cast.	.1875	Bismuth.	.4000
Wire.	.1930	Ice.	1.1250
Caoutchouc.	.657-	Iron.	.3550
	.686	Porcelain.	.1080
	.0118	Sulphur.	2.2373
Carbon { Diamond.	.0540		
Gas carbon.	.0786		
Graphite.	.2078		
Anthracite.	.1678		
Copper.	.842		
Ebonite.	.1836		
German silver.	.0833		
	.0891		
Glass { Tube.	.0897		
Plate.	.0788		
Crown.	.51		
Flint.	.1210		
Ice.	.1061		
	.1140		
Iron { Soft.	.1322		
Cast.	.1095		
Wrought.	.2924		
Steel.	.2508		
Annealed.	.2694		
Lead.	.1012		
Lead-tin (solder).	1.0662		
Magnesium.	.0899		
Nickel.	.0413		
Paraffin.	.0026		
Platinum.	.1921		
Porcelain.	.6413		
Quartz glass.	.2234		
Silver.			
Sulphur.			
Tin.			
Wood, parallel to fiber:			
Oak.			
Pine.			
Across fiber, Oak. .			
Pine.			
Zinc.			

* To obtain linear coefficient divide by 10,000.

† To obtain cubical coefficient divide by 1000.

TABLE VIII

TABLE OF MELTING- AND BOILING-POINTS AND
LATENT HEATS

Substance.	Melting Point, Deg. C.	Latent Heat of Fusion.				Boiling Point, Deg. C.	Latent Heat of Vaporiza- tion.	
		B.T.U per Lb.	Ft.-lbs. per Lb.	Cal. per Gm.	Ergs per Gm.		B.T.U	Cal.
Alcohol, ethyl....	-112	...	.....	.....	.....	77.9	369	205
" methyl....	.....	...	.....	.....	.....	66		
Aluminium.....	658	...	.....	76.8	.....	2300		
Ammonia.....	-75.5	...	.....	108	.....	-34	529	294
Antimony.....	632	...	.....	.....	.....	1535*		
Benzine.....	.....	...	.....	.....	.....	80.1	167	92.9
Bismuth.....	268	22.7	17,640	12.6	52.9×10^7	1300		
Bromine.....	7.1	29.2	22,680	16.2	68.0×10^7	61	...	46
Cadmium.....	321	24.7	19,180	13.7	57.5×10^7	746		
Carbon dioxide..	-80	...	.....	.....	.....			
Copper (in reduc- ing atmosphere)	1084	...	.....	.....	.....	2100		
Copper (in air)...	1064	...	.....	.....	.....			
Gold.....	1064	...	.....	.....	.....	2530*		
Hydrogen.....	-257	28.8	22,400	16.0	67.2×10^7	-252.5		
Iron, pure.....	1510 {	...	.....	.....	.....	about 2420		
" cast gray....	.....	41.4	32,200	23.0	96.6×10^7			
" cast white....	.....	59.4	46,200	33.0	138.6×10^7			
Lead.....	327	9.7	7,560	5.4	22.7×10^7	1800		
Mercury.....	-39	5.4	3,920	2.8	11.8×10^7	357	112	62
Nickel.....	1427	8.3	6,440	4.6	19.3×10^7			
Nitrogen.....	-214	...	.....	.....	.....	-193		
Oxygen.....	-238	...	.....	.....	.....	-182.5		
Platinum.....	1740	49.0	38,080	27.2	114.2×10^7	2450*		
Silver (free from oxygen).....	about 962	38.0	29,540	21.1	88.6×10^7	{ 2400* 2040		
Sulphur.....	115	...	.....	9.4	.....	440		
Sulphuric acid...	10.4	...	.....	.....	.....	338		
Tantalum.....	2910	...	.....	.....	.....			
Tin.....	about { 232	25.7	20,020	14.3	69.1×10^7	1450 to 1600		
Tungsten.....	3080	...	.....	.....	.....	3700*		
Zinc.....	about 419	50.6	39,340	28.1	118.2×10^7	930		
Water (pure)....	0.0	144	112,000	80	336.0×10^7	100	970	539

* Sublimes.

TABLE IX*

STEAM TABLES

1	2	3	4	5	6	7	8	9
Pressure, Lbs. per Sq.in.	Temp. Fahr.	Total Heat Energy.	Specific Volume, Cu.ft. per Lb.	Density, Lbs. per Cu.ft.	Heat Energy of Liquid.	Energy of Vaporiz- ation.	Inter- nal Heat Energy.	Exter- nal Work.
.088	32.00	1071.7	3308	.000302	0.0	1071.7	1017.5	54.2
.100	35.02	1073.2	2952	.000340	3.0	1070.2	1015.6	54.6
.150	45.42	1078.2	2005	.000498	13.5	1064.7	1009.1	55.6
.200	53.14	1081.8	1526	.000650	21.2	1060.6	1004.2	56.4
.300	64.48	1087.3	1039	.000995	32.6	1054.7	997.1	57.6
.400	72.91	1091.2	790	.001265	41.0	1050.2	991.8	58.5
.500	79.68	1094.5	640	.001562	47.8	1046.7	987.4	59.3
.600	85.35	1097.1	538	.001822	53.4	1043.7	983.9	59.8
.700	90.18	1099.4	443	.002119	58.3	1041.1	980.8	60.3
.800	94.48	1101.4	411	.002435	62.6	1038.8	978.0	60.7
.900	98.34	1102.9	367.7	.002719	66.3	1036.6	975.5	61.1
1.00	101.8	1104.5	331.1	.003002	69.	1034.7	973.1	61.6
1.25	109.4	1107.8	269.5	.003710	77.4	1030.4	968.1	62.3
1.50	115.8	1110.6	227.0	.004405	83.8	1026.8	963.8	63.0
1.75	121.3	1112.9	196.4	.00509	89.3	1023.6	960.0	63.6
2.00	126.2	1116.1	173.1	.00578	94.2	1021.9	957.8	64.1
2.50	134.5	1118.7	140.5	.00712	102.5	1016.2	951.3	65.0
3.00	141.5	1121.8	118.4	.00845	109.6	1012.2	946.4	65.8
3.50	147.6	1125.2	102.5	.00975	116.6	1008.6	942.3	66.4
4.00	153.0	1126.5	90.4	.01106	121.0	1005.5	938.6	66.9
5.00	162.3	1130.3	73.3	.01364	130.3	1000.0	932.1	67.9
6.00	170.1	1133.6	61.9	.01616	138.1	995.5	926.8	68.7
7.00	176.8	1136.3	53.6	.01866	144.9	991.4	922.0	69.4
8.00	182.9	1138.7	47.26	.02116	150.9	987.8	917.8	70.0
9.00	188.3	1140.9	42.36	.02362	156.4	984.5	914.0	70.5
10.0	193.2	1142.7	38.37	.02606	161.3	981.4	910.4	71.0
11.0	197.7	1144.5	35.11	.02848	165.9	978.6	907.1	71.5
12.0	202.0	1146.1	32.40	.03088	170.1	976.0	904.1	71.9
13.0	205.9	1147.7	30.06	.03327	174.1	973.6	901.3	72.3
14.0	209.6	1149.0	28.03	.03567	177.8	971.2	898.6	72.6
15.0	213.0	1150.4	26.28	.03805	181.3	969.1	896.2	72.9
16.0	216.3	1151.6	24.74	.04042	184.6	967.0	893.8	73.2
17.0	219.4	1152.8	23.38	.04277	187.8	965.0	891.5	73.5

Heat energy in this table is given in British Thermal Units.

* Adapted from Professor Cecil H. Peabody's "Tables of the Properties of Steam."

TABLE IX—*Continued*

1	2	3	4	5	6	7	8	9
Pressure, Lbs. per Sq.in.	Temp. Fahr.	Total Heat Energy.	Specific Volume, Cu.ft. per Lb.	Density Lbs. per Cu.ft.	Heat Energy of Liquid.	Energy of Vaporiza- tion.	Internal Heat Energy.	External Work.
18.0	222.4	1153.9	22.17	.04511	190.8	963.1	889.3	73.8
19.0	225.2	1154.9	21.07	.04746	193.7	961.2	887.2	74.0
20.0	228.0	1155.8	20.09	.04978	196.4	959.4	885.1	74.3
21.0	230.6	1156.8	19.19	.0521	199.1	957.7	883.1	74.6
22.0	233.1	1157.6	18.37	.0544	201.6	956.0	881.2	74.8
23.0	235.5	1158.5	17.62	.0568	204.1	954.4	879.4	75.0
24.0	237.9	1159.3	16.92	.0591	206.4	952.9	877.7	75.2
26.0	242.3	1160.8	15.70	.0637	210.9	949.9	874.4	75.5
28.0	246.4	1162.2	14.67	.0682	215.1	947.1	871.2	75.9
30.0	250.3	1163.5	13.74	.0728	219.1	944.4	868.2	76.2
32.0	251.1	1164.7	12.93	.0773	222.9	941.8	865.2	76.6
34.0	257.6	1165.9	12.21	.0819	226.5	939.4	862.5	76.9
36.0	261.0	1167.0	11.58	.0864	229.9	937.1	859.9	77.2
40.0	267.3	1169.0	10.49	.0953	236.4	932.6	855.0	77.6
45.0	274.5	1172.2	9.387	.1065	244.7	927.5	849.3	78.2
50.0	281.0	1173.2	8.507	.1176	250.4	922.8	844.1	78.7
55.0	287.1	1175.0	7.778	.1286	256.6	918.4	839.2	79.2
60.0	292.7	1176.7	7.166	.1395	262.4	914.3	834.7	79.6
65.0	298.0	1178.2	6.647	.1504	267.8	910.4	830.4	80.0
70.0	303.0	1179.5	6.199	.1613	272.9	906.6	826.3	80.3
80.0	312.1	1182.0	5.466	.1829	282.2	899.8	818.9	80.9
90.0	320.3	1184.2	4.886	.2047	290.7	893.5	812.1	81.4
100.0	327.9	1186.1	4.432	.2256	298.5	887.6	805.7	81.9
110.0	334.8	1187.7	4.047	.2471	305.6	882.1	799.7	82.4
120.0	341.3	1189.2	3.723	.2686	312.3	876.9	794.2	82.7
130.0	347.4	1190.7	3.451	.2898	318.6	872.1	789.0	83.1
140.0	353.1	1191.8	3.220	.3106	324.4	867.4	784.0	83.4
150.0	358.5	1193.0	3.014	.3318	330.0	863.0	779.3	83.7
160.0	363.6	1194.1	2.834	.3528	335.3	858.8	774.9	83.9
180.0	373.2	1196.1	2.531	.3951	345.2	850.9	766.5	84.4
200.0	381.9	1197.8	2.288	.4371	354.3	843.5	758.8	84.7
225.0	391.9	1199.6	2.043	.4894	364.7	834.9	749.8	85.1
250.0	401.1	1201.1	1.845	.542	374.2	826.9	741.5	85.4
275.0	409.6	1202.6	1.681	.595	383.1	819.5	734.0	85.5
300.0	417.5	1203.7	1.542	.649	391.3	812.4	726.8	85.6
336.0	427.9	1205.2	1.377	.726	402.2	803.0	717.4	85.6

TABLE X *
PRESSURE-ENTROPY

Tem. Fahr.	Pressure in Lbs. per sq. in.	1.52			1.58			1.64		
		Qual- ity.	Total Energy.	Spec- ific Vol.	Qual- ity.	Total Energy.	Spec- ific Vol.	Qual- ity.	Total Energy.	Spec- ific Vol.
420	309	10.7	1213	1.54	101	1268	1.78	224	1331	2.09
400	247	991	1193	1.85	71.6	1246	2.11	186	1306	2.46
390	220	982	1184	2.05	57.9	1236	2.30	167	1294	2.68
380	196	972	1174	2.27	43.9	1225	2.52	149	1281	2.92
370	173	966	1164	2.53	30.0	1214	2.77	130	1269	3.20
360	153	955	1154	2.83	16.3	1203	3.05	112	1257	3.50
350	135	946	1144	3.16	2.7	1193	3.36	94.7	1244	3.86
340	118	938	1134	3.55	992	1182	3.75	77.1	1232	4.28
330	103	929	1124	4.01	983	1171	4.24	59.8	1219	4.74
320	89.6	921	1113	4.52	973	1160	4.78	42.6	1207	5.27
310	77.6	913	1103	5.13	964	1149	5.42	25.4	1195	5.86
300	67.0	904	1092	5.85	955	1137	6.17	8.1	1183	6.56
290	57.5	896	1081	6.68	945	1126	7.05	995	1171	7.42
280	49.2	889	1070	7.68	937	1114	8.09	985	1159	8.50
270	41.8	881	1059	8.85	928	1102	9.32	975	1146	9.80
260	35.4	873	1047	10.3	919	1091	10.8	965	1134	11.3
250	29.8	865	1036	12.0	910	1079	12.6	955	1121	13.2
240	25.0	857	1024	14.0	902	1066	14.7	946	1108	15.4
230	20.8	850	1013	16.5	893	1054	17.3	936	1095	18.1
220	17.2	842	1001	19.5	885	1042	20.5	927	1082	21.5
212	14.7	836	991	22.4	878	1031	23.5	919	1072	24.6
200	11.5	827	977	27.8	868	1016	29.2	908	1056	30.5
180	7.51	812	952	40.8	851	990	42.7	890	1028	44.7
160	4.73	797	926	61.5	834	964	64.4	871	1001	67.3
150	3.72	790	913	76.5	824	950	80.0	862	987	83.5
145	3.28	786	907	85.6	822	943	89.6	858	979	93.5
140	2.88	782	900	96.0	818	936	100	853	972	105
135	2.53	778	894	108	813	929	113	848	965	118
130	2.22	774	887	122	809	922	127	844	958	133
125	1.94	771	880	137	805	915	144	839	950	150
120	1.69	767	873	156	801	908	163	835	943	169
115	1.47	763	867	177	796	901	185	830	936	192
110	1.27	759	860	201	792	894	210	825	928	220
105	1.10	755	853	230	788	887	240	821	921	250
100	.95	751	846	264	784	879	275	816	913	286
95	.81	747	839	303	779	872	315	811	906	328
90	.70	743	832	349	775	865	364	807	898	379
85	.60	739	825	402	771	858	419	802	890	436
80	.51	736	818	466	766	850	486	797	883	505
70	.363	728	803	632	758	835	658	789	867	684
60	.256	720	789	849	749	820	884	779	851	919
32	.089	697	747	.....	725	776	.....	752	806	...

Heat energy in this table is given in British Thermal Units.

* Adapted from Professor Cecil H. Peabody's "Tables of the Properties of Steam."

TABLE X—Continued

1.70			1.76			1.82			Pressure in Lbs.	Tem. Fahr.
Qual- ity.	Total Energy.	Spec- ific Vol.	Qual- ity.	Total Energy.	Spec- ific Vol.	Qual- ity.	Total Energy.	Spec- ific Vol.		
									309	420
									247	400
									220	390
295	1358	3.08								
274	1344	3.36							196	380
252	1330	3.68							173	370
231	1316	4.04							153	360
210	1302	4.44							135	350
189	1288	4.91							118	340
167	1274	5.44							103	330
146	1260	6.05	266	1319	6.90				89.6	320
125	1246	6.75	241	1303	7.68				77.6	310
104	1232	7.54	217	1287	8.60				67.0	300
83.6	1218	8.46	192	1271	9.66				57.5	290
62.9	1204	9.51	168	1255	10.9	287	1313	12.4	49.2	280
42.1	1191	10.07	144	1240	12.3	260	1296	14.0	41.8	270
21.6	1177	12.2	120	1225	14.0	232	1278	15.9	35.4	260
0.6	1164	13.8	96.1	1209	15.9	205	1261	18.2	29.8	250
990	1150	16.1	72.0	1194	18.2	177	1244	20.7	25.0	240
979	1137	19.0	48.0	1179	20.8	149	1226	23.9	20.8	230
969	1123	22.4	24.2	1164	24.0	122	1209	27.6	17.2	220
961	1112	25.7	5.0	1152	27.0	100	1196	31.1	14.7	212
949	1095	31.9	989	1135	33.3	68.3	1176	37.4	11.5	200
929	1067	46.6	967	1105	48.6	14.6	1144	51.2	7.51	180
909	1038	70.1	946	1075	73.0	983	1112	75.9	4.73	160
899	1023	87.1	935	1060	90.6	971	1096	94.1	3.72	150
894	1016	97.4	929	1052	101	965	1088	105	3.28	145
889	1008	109	924	1044	113	960	1080	118	2.88	140
884	1001	123	919	1036	128	954	1072	132	2.53	135
879	993	138	913	1028	144	948	1064	149	2.22	130
874	985	156	908	1021	162	942	1056	168	1.94	125
869	978	176	903	1013	183	936	1047	190	1.69	120
864	970	200	897	1005	208	931	1039	216	1.47	115
858	962	228	892	996	236	925	1031	245	1.27	110
853	955	260	886	988	270	919	1022	280	1.10	105
848	947	298	881	980	309	913	1014	320	.95	100
843	939	341	875	972	354	907	1005	367	.81	95
838	931	393	870	964	408	902	997	423	.70	90
833	923	453	865	956	470	896	988	487	.60	85
828	915	525	859	947	545	890	980	564	.51	80
818	899	710	849	931	737	879	962	763	.363	70
808	883	954	838	914	988	867	945	.....	.256	60
780	836	.....	807	865	.....	835	895	.....	.089	32

TABLE XI
SPECIFIC HEAT OF STEAM

Pressure in lbs. per sq.in.	14.2	50	100	150	200	250	300
Temp. superheat F. 212°..	.46						
“ “ 300°..	.46	.51					
“ “ 400°..	.46	.50	.54	.60	.67		
“ “ 500°..	.46	.49	.53	.55	.59	.63	.67
“ “ 600°..	.47	.49	.51	.53	.55	.57	.59
“ “ 700°..	.47	.49	.51	.52	.53	.55	.56

TABLE XII
TEMPERATURES OF HOT BODIES

Source.	Degree C.	Observer and Method.
Incandescent electric lamp (carbon).....	1800	Le Chatelier, optical pyrometer
Arc lamp.....	4100	“ “ “
Arc lamp.....	3760	Fery, heat radiation pyrometer
Thermit in mold.....	2500	“ “ “
Bunsen flame, open.....	1870	Fery, spectroscopic method
Bunsen flame, closed.....	1710	“ “ “
Acetylene flame.....	2550	“ “ “
Oxy-hydrogen flame.....	2420	“ “ “
Melting-point of tantalum..	3000	Waidner and Burgess, optical pyrometer
Melting-point of tungsten..	3200	do. do.
Temperature of sun.....	7600	Le Chatelier, optical pyrometer
Temperature of sun.....	7500	Fery, heat-radiation pyrometer

TABLE XIII
WAVE LENGTHS

	Millionths of cm.
Shortest ultra-violet waves.....	10
Shortest visible waves (violet), about.....	38
Violet, about.....	40
Blue.....	45
Green.....	52
Yellow.....	57
Red.....	65
Longest visible waves (red).....	75
Longest waves in solar spectrum, more than....	530
Longest waves transmitted by fluorite.....	950
Longest waves by selective reflection from rock salt.....	5,000
By reflection from potassium chloride.....	6,120
Shortest electric waves.....	600,000

TABLE XIV
THERMAL CONDUCTANCE *

	Temp. Range, Cent., Deg.	Ohms, Thermal Resistance.		Thermal Conductance or Conductivity.		
		Inch. Cube.	Cm. Cube.	Mho.	Cm. Cube Calorie Unit.	British† Units per Hr.
Air.....	at 0	.....	2000	.0005	.0001	.35
Aluminium.....		.....	.73	1.5	.35	1000
Asbestos { From.....		139	353	.0028	.0007	1.96
{ to.....		416	1060	.0009	.0002	.65
Boiler scale.....	at 60	17	44	.023	.006	16
Brick { From.....		21	53	.019	.0045	13
{ to.....		62	160	.0063	.0014	4.4
Carbon (electrode)....	100 to					
360		1.05	2.7	.37	.088	260
Charcoal.....	at 50	603	1530	.00065	.00017	.45
Copper.....	0 to 100	0.11	0.27	3.7	.85	2600
Glass.....		87	220	.0046	.0011	3.2
Ice.....		16	42	.024	.0057	17
Infusorial earth { From.....		263	675	.0015	.00036	1.0
{ to.....		745	1890	.0005	.00012	.35
{ Cast { From.....		0.26	0.66	1.5	.36	1000
{ to.....		0.63	1.6	.63	.15	440
{ Steel { From.....		0.24	0.60	1.67	.40	1200
{ to.....		3.0	7.7	.13	.031	90
{ Wrought { From.....		0.22	0.55	1.8	.43	1200
{ to.....		0.79	2.0	.5	.12	350
Lead.....		1.1	2.8	.36	.085	250
Magnesia, calcined....	20 to 155	554	1410	.00071	.00017	.49
Rubber, hard.....		1060	2680	.00037	.00009	.25
Sawdust.....		600	1600	.00063	.00015	.44
Silver.....	0 to 100	0.09	0.24	4.20	1.00	3900
Tin.....		.63	1.59	.63	.153	440
Wood, pine.....		1070	2700	.00037	.00009	.25
" fir along fiber.....		200	500	.0020	.00047	1.38
" fir across fiber.....		360	920	.0011	.00026	.76
Wool, cotton { From.....		572	1460	.0007	.00016	.48
{ to.....		2800	7100	.00014	.00003	.10
" mineral.....	1 to 18	1000	2600	.00038	.00009	.26
" sheep { From.....		620	1600	.00063	.00015	.44
{ to.....		600	2100	.00048	.00011	.33
Zinc.....		.32	.81	1.23	.295	850

* All the values in this table are approximations.

† B.T.U. per hr. per sq.ft. area per in. thickness.

APPENDIX B

NOTE ON CORRECTION OF BAROMETER FOR TEMPERATURE

READINGS taken directly from a barometer must be corrected for several errors before being used in very accurate determinations. Among the corrections necessary are those for temperature, for capillarity, and for vapor pressure in the tube above the mercury. Of these, the correction for temperature is the most important and is the only one which will be made in any of the experiments given in this course, unless the student is otherwise directed by the instructor.

To read the laboratory barometer and correct this reading, proceed as follows: First adjust the height of mercury in the cistern until the surface is just in contact with the point of the ivory index. Then read the height of the mercury column with the vernier of the instrument, and take the temperature of the mercury as given by the thermometer in the case. The true height of the barometer is its height at 0° C. Since mercury expands .00018 of its volume for each degree C.,

$$\text{reading at } 0^{\circ} \text{ C.} = h - .00018ht,$$

when t = temperature (centigrade) of the mercury as obtained from the thermometer of the instrument, and h = observed height.

A further correction is made necessary by the expansion of the brass scale if it be graduated at 0° C. Brass

expands .000019 of its length for each degree C. Making this correction we have:

$$\text{true height} = h - (.00018 - .000019)ht.$$

PROBLEM. Barometer reads 14.48 lbs. at 23.4° C. Reduce to 0° C.

APPENDIX C

SIGNIFICANT FIGURES

(Revised and reprinted with permission from Jameson's "Mechanics."
Longmans, Green & Co.).

IN practical computation, figures should not be used *blindly* according to the simple rules of arithmetic. We often use what we sometimes call *round numbers* when we are working roughly and not with absolute certainty. In industrial and technical computations we are never *absolutely* exact. Approximate information and approximate results are all we ever have. The more scientifically we work the more carefully must we recognize and indicate the *degree of accuracy* of our work.

Significant figures are figures which we *know to represent with reasonable certainty* some real condition or quantity. Significant figures give *all* the information which we have without giving any of which we are not reasonably certain. In other words, they are figures which really mean something.

The student must observe carefully the following rules in all laboratory work and reports. These same rules should always be applied to recording scientific or technical data. These rules must be applied, however, with judgment, as they are intended merely as a guide to judgment rather than as orders to be followed blindly. The following examples illustrate the use of significant figures:

I. RECORDING READINGS

In general, scales, etc., are to be read to tenths of the smallest divisions marked on the instrument. The last

figure entered in the record is thus assumed always to be an estimation and *therefore doubtful*.

Example 1. 15.57 cms. means that a distance was measured by a scale subdivided to *millimeters*, and that the observer *estimated* the seven; thus the distance is known to be between 15.5 and 15.6, and *estimated* to be $\frac{7}{10}$ the way between these two values. It is misleading, and furnishes only a clue to what we *actually know* about this distance to record it as 15.6 or 15.570 cm.

Example 2. A distance is being measured with a rule subdivided to *tenths of inches*. The observer finds the distance to be as nearly exactly seven inches as *he can distinguish*. This should be recorded 7.00 in. (not 7.0 or 7 ins.). Why?

Example 3. A balance is capable of weighing an object to .01 gm. and .001 gm. can be estimated. Notice the correct records for following:

Eight gms.....	8.000 gms.
Eight and $\frac{1}{4}$ gms.....	8.250 gms.
Eight and $\frac{7}{100}$ gms.....	8.070 gms.
Eight and $\frac{8}{1000}$ gms.....	8.008 gms.
Eight-tenths gm.....	.800 gm.

In general a series of readings made with the same instrument should all show the same number of places filled in to the right of the decimal point *even if one or all these places are zeros*. Why?

It is often convenient to express *in decimal form*, readings taken from scales divided into halves of units, quarters, eighths, etc. In all such cases, retain only as many places in the decimal as correspond approximately to the same degree of precision as would be expressed by the fraction, i.e., to the nearest half unit, to the nearest quarter, etc. If the first decimal figure rejected is 5 or greater, call the preceding figure one larger than before. For example:

$\frac{1}{2} = .5$ when the reading merely means that it is somewhere between zero and unity.

If by $\frac{1}{2}$ the observer is certain that the reading is nearer $\frac{1}{20}$ than it is $\frac{9}{20}$ or $\frac{1}{20}$, then the true decimal equiv. = .50.

$\frac{1}{3} = .3$ except when the observer is sure that it is nearer $\frac{1}{30}$ than is $\frac{9}{30}$ or $\frac{1}{30}$ when the true decimal equiv. = .33.

$\frac{1}{4} = .3$, but when the values are such that $\frac{1}{4} > \frac{9}{40}$ but $< \frac{11}{40}$, then decimal equiv. = .25.

$\frac{1}{5} = .2$ and not .20 except under similar conditions as above.

$\frac{1}{6} = .2$ and not .1667, etc.

$\frac{1}{8} = .1.$	$\frac{3}{8} = .4.$	$\frac{7}{8} = .7.$
$\frac{1}{16} = .06.$	$\frac{5}{8} = .6.$	$\frac{3}{4} = .8.$
$\frac{1}{32} = .03.$	$\frac{7}{8} = .9.$	$\frac{3}{16} = .19.$

II. USE OF DATA IN CALCULATIONS

Wherever the figure following the doubtful (last retained) figure is 5 or greater than 5, increase the doubtful figure by unity. Thus, if but three figures are to be kept, 15.75, 15.76, 15.77, 15.78, and 15.79 would all be entered 15.8.

Notice especially that the *location of the decimal point has nothing to do with significant figures*. Thus, 275, 27.5, 2.75, .275, .0275, .00275, etc., are all results expressed to the same degree of precision, and in each there are *three and only three* significant figures, the 5 being the doubtful figure in each.

Averages. In averaging a series of determinations, in general, retain in the result the same number of significant figures as in any one item.

But if a *large* number of items closely agreeing with each other are averaged, the result *may* contain *one more* significant figure than any item.

Multiplication. After the operation, keep in the result as many figures, *counting from the left*, as there are sig-

nificant figures in the factor having the *lesser number* of significant figures.

Division. In dividing one number by another, keep in the quotient as many figures as there are significant figures in the number having the lesser number of significant figures. Continue the divisions only far enough to determine the required figures.

Note on Multiplication and Division. Ciphers immediately following the decimal point, *when there are no figures to the left of the point, do not count* as significant. Study the following examples:

$$(a) 15.75 \times 3.08 = 48.5.$$

$$(b) .096 \times .096 = .0092.$$

$$(c) .1523 \times .00113 = .000172.$$

$$(d) 720 \times 3.1 = 2200.$$

The cipher in cases (b), (c), and (d) are not significant.

$$(e) .900 \times .800 = .720.$$

All the ciphers in this case are significant.

$$(f) 900 \times 800 = 720,000.$$

In the product in (f) only the *first cipher* is significant. It is necessary to add the other three to express the number properly.

$$(g) 325.6 \div 72.5 = 4.49.$$

$$(h) .0007859 \div 157 = .00000500.$$

Use of Pure Numbers, Constants, etc. In using pure numbers and constants such as 3.1416, .7854, etc., do not employ more figures than there are significant figures in the experimental data which are used with the constants in the same calculation. Thus if the diameter of a circle is measured as 4.51, the area is $4.51 \times 4.51 \times .785 = 15.9$. The use of more numbers in the constant lengthens the computation and gives no better result. Why?

APPENDIX D

CURVES

CURVES are used to show a large amount of data in a way to make the significance of the information *as a whole* appeal to the eye. Curves are like a picture of the data in that they enable one to view the subject matter as a whole and also to see each detail.

Generally curves show what happens to two quantities which are varying. In the course of experiments in the laboratory the student may have occasion to adjust or vary the temperature of a body, the energy in a body, or some other property or factor within his control. The quantity which the student *alters* is called the independent variable and is usually represented algebraically by the letter X .

As a *result* of the change which takes place in the quantity which is represented by X a change may take place in some other factor or property of matter, and this second variable is usually represented by Y . Thus if X represented the temperature of a gas, then Y might represent the volume of the gas, the density of the gas, or any other property of the gas which was affected by a change of temperature.

(The following is a revision by permission of pp. 305 to 313 of Jameson's "Mechanics," Longmans, Green & Co.)

Coordinate Axes. The position of a single point in space may be fixed by reference to two known straight lines intersecting at right angles in the same plane as the point. Thus P_1 has its position defined by OX and OY of Fig. 78. Such lines are known as *coordinate axes*.

Also the position of a series of points which go to make up a line may be expressed in a similar way.

The horizontal line (OX) is known as the *axis of abscissæ* or " X axis," the vertical line (OY) as the *axis of ordinates* or " Y axis." The *abscissa* of a point is its horizontal distance from OY ; its *ordinate* is the vertical distance from OX . These given, the position of the point is determined. Thus P is that point which has an abscissa of 3, an ordinate of

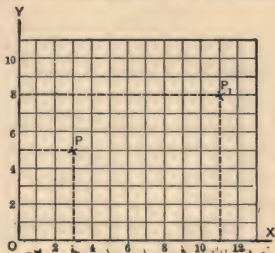


FIG. 78.

5, P_1 the point which has abscissa of 11, ordinate of 8, etc.

The point of intersection of the axes is called the *origin*.

For convenience, squared or *cross-section* paper is used for work of this kind.

Curves. A succession of *related* points may be connected by a smooth line, thus constituting a "*curve*." Such curves are frequently the most convenient and the clearest way of representing a physical law, corrections for errors of apparatus, etc. Suppose, for example, that it is desired to show the relation between the volume of 1 lb. of air and the temperature. Changes in temperature produce changes in volume according to the following data:

Abs. Temperature.	Volume.
461	12.4
550	14.7
625	16.8
700	18.8
775	20.7
900	24.2

Taking the absolute temperature expressed in some convenient scale of lengths, as abscissæ, and the corresponding

volumes, similarly expressed as ordinates, a series of points may be located as just explained, and through these a smooth line may be drawn. Inspection of the curve thus produced (Fig. 79) will show at a glance information which could be obtained from the figures only on more extended analysis. The law, "Volume is proportional to absolute temperature" is seen immediately, from the nature of the curve.

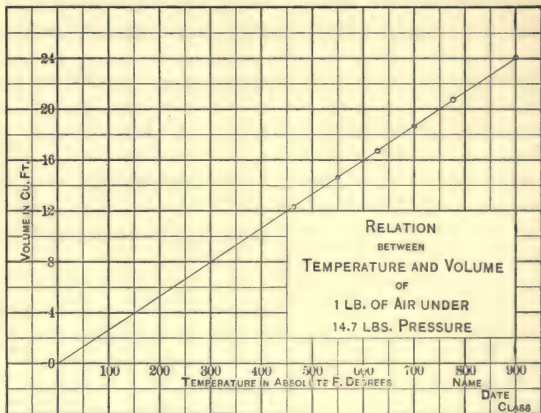


FIG. 79.

Whenever the curve is a straight line and passes through the origin, the quantity plotted on the X axis is in *direct* proportion to the quantity plotted on the Y axis. If the curve is a straight line but does not pass through the origin, the increase in X is in proportion to the increase in Y . This latter proportion may be either direct or inverse. (See the following discussion of the "Equation of a Straight Line" for a proof of the above.)

Had the curve turned continuously more and more toward either the X or the Y axis, showing in one case a

progressive increase, in the other a progressive decrease in volume with increase of temperature, or had, at any time, a sudden change from the conditions which had previously existed occurred, these factors would have been brought to the attention as quickly.

When also, as here, the great majority of points lie along a straight line (or, as in some cases, along a smooth curve), any experimental errors of measurement (as in the volume for 625° and 775°) will be shown at once by the fact that these points lie slightly off the line. In all such cases, the curve should be drawn as nearly as may be through all points, and leaving as many points on one side as on the other.

The student must in all cases use his judgment in drawing the curve and consider the conditions of the experiment and the general physical law illustrated.

It is not necessary, and indeed often not advisable, that ordinates and abscissæ be expressed in the same scale. Of course, for the same curve all abscissæ must be in one scale, and all ordinates in one scale. In general, the scale adopted should be that most convenient for the particular values which will at the same time give a curve as large as the paper will permit.

One, two, five, or ten units to a square will be found the best. Avoid the use of three or seven units per inch, or other inconvenient subdivisions.

GENERAL DIRECTIONS FOR CURVE PLOTTING

1. The curve sheet should have all lines and lettering done neatly in either very hard pencil or **India ink**, as directed by an instructor. Ordinary *black ink* should never be used on a curve sheet. If several curves are to be drawn on the *same* sheet it is permissible to use a different color of ink for each curve.

2. The heavy line **one inch up** from the first ruled line from the bottom and the heavy line **one inch over** from the left side are to be taken as axes. (An exception to this may be made when the inch thus sacrificed is needed.) The origin, i.e., the intersection of vertical and horizontal axes, should be near the lower left-hand corner.

Each axis should start near the lower left-hand corner. The paper may be used with either the longer or shorter side as vertical axis, according to needs of the curve.

3. The scale on which the curve is plotted should be so selected as to **make the curve as large as possible**. The curve should go as far to the right and as high on the paper as the selection of a convenient scale will allow.

4. Each axis should be marked:

(a) With the name of the quantity, the amount of which is represented by distances along it.

For example: The *X* axis might represent temperature.

(b) With the name of the unit in which the quantity is measured. For example: If the *X* axis represents temperature, the unit might be degrees C. The student would then letter, not write, along the ruled line, $\frac{1}{2}$ in. below the axis line the following: "TEMPERATURE IN DEGREES C."

(5) Each *inch* line along both the vertical and the horizontal axis should be numbered with the numerical value which is represented by that distance. No other figures are to be written on the axis line or in any other way used in locating points on the curve.

(6) The points are to be located by a pin prick in the paper and a circle should be drawn around this with a bow pen to enable the point to be more readily found.

(7) The curve should usually be a *smooth line* drawn as nearly as possible through all points. It will represent the most probable average of the observations, and any single point lying at a distance on either side of the line will usually be a result of error in observations. Of course judgment must be used in drawing this conclusion, and the conditions

of the experiment and the nature of the related quantities of the curve must always be taken into account.

In locating the curves, if it is to be a straight line, a rubber band will be found helpful. A transparent straight-edge will be found still better.

The curve is the only line which the student should draw on the coordinate paper.

(8) The *name of the student, the date, and section* should be placed at the bottom of the sheet at the right in small letters.

(9) The title should be given a prominent place.

(10) If more than one curve is drawn on the same paper for comparison, etc., use the same origin and the same abscissa for all. If more than one curve is plotted on the same sheet, distinguish the curves by the title printed along the curve, or by lines of different colors.

(11) All titles, explanations, etc., must be in lettering, and no handwriting should appear upon the curve sheet.

THE EQUATION OF A STRAIGHT LINE

It is often desired to find the equation that corresponds to a given line (straight or curved) plotted on squared paper. In this course it will not be necessary to obtain the equation of a curved line. A simple method for the equation of a straight line follows:

Let AP_3 , Fig. 80, be a line plotted as usual on the axes OX and OY , and meeting the axis of Y at the point A . (If the line as first drawn does not cut the axis of Y it must be extended till it does so.)

At the point A draw a line parallel to the axis of X . Choose any point on the line as P_2 , and draw its ordinate y_2 . x_2 is the abscissa of this point. We desire to obtain an equation that will give us the relation between the abscissa and the ordinate for this and every other point on this line.

We notice first that the ordinate y_2 equals the intercept OA on the Y axis, plus P_2D_2 , or

$$y_2 = OA + P_2D_2.$$

Also,

$$y_1 = OA + P_1D_1,$$

$$y_3 = OA + P_3D_3,$$

and so on for every point on the line.

The value of the *intercept* OA may now be read from the curve. Suppose in the given case $OA = 8$. Next read

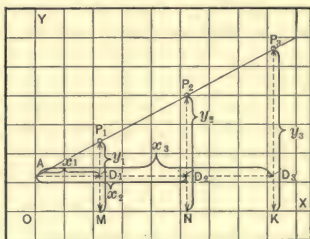


FIG. 80.

from the curve *values* of the *altitude* and *base* of *any triangle* whose hypotenuse is some part of the line AB . These values are to be expressed in units of the respective scales used in plotting X and Y and *not* as actual lengths in inches. The triangle AP_2D_2 will serve. Suppose $P_2D_2 = 4$ and $AD_2 = 10$ in the given case. Then $\frac{P_2D_2}{AD_2} = .4$. But

$AD_2 = x_2$, therefore, $P_2D_2 = .4x_2$.

If we had used other triangles we should have obtained the *same ratio* between altitude and base, and thus,

$$P_1D_1 = .4x_1,$$

$$P_2D_2 = .4x_2,$$

$$P_3D_3 = .4x_3.$$

Or, in words, we may now say that any ordinate equals the intercept on the Y axis plus .4 of the abscissa for the same point. Let x and y be the coordinates of *any point on the line AB* ; then

$$y = 8 + .4x,$$

which is the equation desired.

The ratio $\frac{P_2D_2}{AD_2}$ is sometimes called the *slope* of the line.

We may now state the general *rule* as follows:

RULE. The equation of a straight line is formed by putting y equal to the intercept on the axis of Y plus the slope times x . If intercept = a , and slope (ratio) = m , we have,

$$y = a + mx.$$

NOTE. The student will notice that the equation just given is perfectly general. If the line cuts the axis of Y *below* the origin, the intercept will be a *negative* term and the equation will be of the form $y = -a + mx$. If the line slopes so that an increase in the value of the abscissa causes a decrease in the value of the ordinate, then m will be a negative quantity, $y = a - mx$. It is possible, of course, that both a and m may be negative at the same time, as $y = -a - mx$. The student should draw and consider carefully lines to illustrate each case.

APPENDIX E

FROM PRELIMINARY REPORT OF THE POWER TEST COMMITTEE OF THE A.S.M.E.

CALCULATION OF RESULTS

THE methods to be followed in expressing and calculating those results which are not self-evident are explained as follows:

(a) *Efficiency.* The "efficiency of boiler, furnace, and grate" is the relation between the heat absorbed per pound of coal fired, and the calorific value of one pound of coal.

The "efficiency of boiler and furnace" is the relation between the heat absorbed per pound of combustible burned, and the calorific value of one pound of combustible. This expression of efficiency furnishes a means for comparing one boiler and furnace with another, when the losses of unburned coal due to grates, cleanings, etc., are eliminated.

The "combustible burned" is determined by subtracting from the weight of coal supplied to the boiler, the moisture in the coal, the weight of ash and unburned coal withdrawn from the furnace and ashpit, and the weight of dust, soot, and refuse, if any, withdrawn from the tubes, flues, and combustion chambers, including ash carried away in the gases, if any, determined from the analyses of coal and ash. The "combustible" used for determining the calorific value is the weight of coal less the moisture and ash found by analysis.

The "heat absorbed" per pound of coal, or combustible, is calculated by multiplying the equivalent evaporation from and at 212 deg. per lb. of coal or combustible by 970.4.

(b) *Corrections for Moisture in Steam.* When the percentage is less than 2 per cent it is sufficient merely to deduct the percentage from the weight of water fed. If the percentage is greater than 2 per cent or if extreme accuracy is required, the factor of correction equals

$$Q + P \frac{(T-h)}{(H-h)},$$

in which Q is the quality of the steam (one minus the decimal representing the percentage of moisture), P the proportion of moisture, T the total heat of water at the temperature of the steam, h the total heat of the feed water, and H the total heat of saturated steam of the given temperature.

(c) *Correction for Live Steam, if any, Used for Aiding Combustion.* If live steam is admitted into the furnace or ashpit for producing blast, injecting fuel, or aiding combustion, it is to be deducted from the total evaporation, and the net evaporation used in the various calculations.

(d) *Equivalent Evaporation.* The equivalent evaporation from and at 212 deg. is obtained by multiplying the weight of water evaporated, corrected for moisture in steam, by the "factor of evaporation." The latter equals

$$\frac{H-h}{970.4}$$

in which H and h are respectively the total heat of saturated steam and of the feed water entering the boiler. When the steam is superheated, the total heat of the steam is that of saturated steam plus the product of the number of degrees of superheating by the specific heat of the steam.

Unless otherwise provided, a combined boiler and superheater should be treated as one unit, and the equivalent of the work done by the superheater should be included in the evaporative work of the boiler.

(e) *Heat Balance.* The "heat balance," or approximate distribution of the calorific value of the coal or combustible among the several items of heat utilized and heat lost, should be obtained in cases where the flue gases have been analyzed and a complete analysis made of the coal.

The loss due to moisture in the coal is found by multiplying the total heat of one pound of superheated steam at the temperature of the escaping gases, calculated from the temperature of the air in the boiler room, by the proportion of moisture.

The loss due to moisture formed by the burning of hydrogen is obtained by multiplying the total heat of one pound of superheated steam at the temperature of the escaping gases, calculated from the temperature of the air in the boiler room, by the proportion of the hydrogen, determined from the analysis of the coal, and multiplying the result by 9.

The loss due to heat carried away in the dry gases is found by multiplying the weight of gas per pound of coal or combustible by the elevation of temperature of the gases above the temperature of the boiler room, and by the specific heat of the gases (0.24). The weight of gas referred to is obtained by finding the weight of dry gas per pound of carbon burned, using the formula

$$\frac{11 \text{ CO}_2 + 8 \text{ O} + 7(\text{CO} + \text{N})}{3(\text{CO}_2 + \text{CO})},$$

in which CO_2 , CO , O , and N are expressed in percentages by volume, and multiplying this result by the proportion borne by the carbon burned to the whole amount of coal or combustible as determined from the results of the analysis of the coal, ash, and refuse.

The loss due to incomplete combustion of carbon is found by first obtaining the proportion borne by the carbon monoxide in the gases to the sum of the carbon monoxide and carbon dioxide, and then multiplying this proportion by the proportion of carbon in the coal or combustible, and finally multiplying the product by 10,150, which is the number of heat units generated by burning to carbon dioxide one pound of carbon contained in carbon monoxide.

The loss due to combustible matter in the ash and refuse is found by multiplying the proportion that this combustible bears to the whole amount of coal or combustible, by its calorific value per pound. For most purposes it is sufficient to assume the latter to be 14,600 B.T.U., the same as that of carbon.

The loss due to moisture in the air is determined by multiplying the weight of such moisture per pound of coal or combustible by the elevation of temperature of the flue gases above the temperature of the boiler room and by 0.47. The weight of moisture is found by multiplying the weight of air per pound of coal or combustible by the moisture in one pound of air determined from readings of the wet and dry-bulb thermometer.

(f) *Total Heat of Combustion of Coal, by Analysis.* The total heat of combustion may be computed from the results of the ultimate analysis by using the formula

$$14,600 \text{ C} + 62,000 \left(\text{H} - \frac{\text{O}}{8} \right) + 4000 \text{ S},$$

in which C , H , O , and S refer to the proportions of carbon, hydrogen, oxygen, and sulphur, respectively.

(g) *Air for Combustion.* The quantity of air used may be calculated by the formulæ:

$$\text{Lb. of air per lb. of carbon} = \frac{3.032 \text{ N}}{\text{CO}_2 + \text{CO}}.$$

in which N, CO₂, and CO are the percentages of dry gas obtained by analysis, and

Lb. of air per lb. of coal = lb. air per lb. C × per cent C in the coal.

The ratio of the air supply to that theoretically required for complete combustion is $\frac{\text{N}}{\text{N} - 3.782 \text{ O}}$.

INDEX

- Absolute Pressure, 130
 - " Temperature, 81
- Acetylene, 31
- Adiabatic Expansion, 204
- Air, Expansion of, 83
 - " for Combustion, 29, 324
 - " Liquefier, 259
 - " Pumps, 146
- Alcohols, 28, 37
- Alcohol Thermometers, 274
- Aluminum Powder, 35
 - " Specific Heat of, 52
- Ammonia Cycle, 252
- Anthracite, 28
- Anthracite Coal, 36
- Argon, 29
- Asbestos, 234
- Ash, 27
- Atom, 10
- Autoclaves, 121
- Axis, Coordinate, 313

- Back Pressure, 165
- Baffle, 157
- Barnes, H. T., 17
- Batteries, 6
- Benzine, 29
- Bituminous Coal, 28
- Black Body Radiations, 239
- Blowers, 146
- Boiler, 36, 139, 154
 - " Babcock & Wilcox, 154
 - " Efficiency, 158, 235
 - " Horse-power, 157
 - " Sterling, 155
- Boiling, Defined, 112
 - " Point, 106, 124
 - " " Defined, 112
 - " " Experimentally determined, 115

- Bolometer, 238, 279
- Bomb Calorimeter, 284
- Bore of Thermometer, 270
- Boyle's Law, 74, 90, 203
- Brine, 249
- Bristol Pyrometers, 279
- British Thermal Unit, 15

- Calculations, 311
- Calibration of Thermometer, 270
- Callendar, Hugh L., 17
- Calorie, 15
- Calorimeters,
 - " Bomb, 284
 - " Fuel, 283, 299
 - " Separating, 293
 - " Throttling, 291
- Calorimetry, 47, 50
- Camera, 238
- Carbon, 30
 - " Dioxide, 28, 29
 - " Monoxide, 29
- Carbureter, 9, 179
- Carnot's Cycle, 170
- Centigrade, 13
- Charcoal, 28, 234
- Charles' Law, 76, 90
- Chimney, Draft of, 225
- Chromium, Oxides of, 35
- Clinker, 27, 36
- Coal, 4
 - " Anthracite, 36
 - " Bituminous, 28
 - " Gas, 37
 - " Purchasing, 36
- Coke, 28
- Combustion, Air for, 29, 324
- Complete Analysis, 28
- Compression Type of Refrigerating Plant, 247

- Compressor, 247
 Condensation, Defined, 112
 Condenser, 119, 146, 247
 " Alberger Barometric, 167
 " Jet or Barometric, 163
 " Surface, 163, 165
 " Wheeler-Admiralty Surface, 163
 Conductance, 229
 Conduction, 223, 227
 Conductivity, 230
 Constants, 312
 Convection, 223
 Cook Stoves, 242
 Cooling Towers, 120
 Coordinate Axes, 313
 Cost Economy, 145
 " Efficiency, Defined, 178
 Critical Pressure, Defined, 114
 " Temperature, 107
 " " " " , Defined, 114
 Crosby Indicator, 288
 Crude Oil, 37
 Cryogens, 257
 Curves, 313
 Cycle, 180
 " Carnot's, 170
 " Rankine, 170
 Cylinder, 9

 Dalton's Law, 114
 Density, 94
 Deviations, 51, 55
 Dew, Defined, 114
 " Point, Defined, 113
 Dewar Bulb, 243, 263
 Diesel Cycle, 180
 Distillation, 118
 " Fractional, 119
 Draft, 27
 " of Chimney, 225

 Economizer, 146, 150, 160
 Effective Pressure, 141
 Efficiency, 38
 " of Boilers, 158, 235
 " Fuel, 158
 " Furnace, 235
 Electrical Equivalent Apparatus, 18, 21
 Electrons, 11
 Energy, Chemical, 5
 Energy, Defined, 1
 " Diagram, 145, 148, 188, 250
 " Efficiency, 178
 " Electrical, 4, 5, 6, 9
 " in Gases, 209
 " Kinetic, 3
 " Light, 4, 7
 " Mechanical, 5
 " of Fuels 31
 " Motion, 2
 " Potential, 4
 " Stream of, 149, 152, 188, 250
 Engine, 9, 140
 " Cycles, 211
 " Four-cycle, 180
 " Two-cycle, 180
 Entropy, 214
 Equation of Straight Line, 318
 Equivalent Evaporation, 235
 Errors, 51
 Ether Waves, 7
 Ethylene, 29
 Evaporation, 107
 " Defined, 112
 " Factor of, 157
 Evaporator, 249
 Exceptional Fuels, 35
 Expansion, Cubical, 70
 " Isothermal, 74
 " Joint, 65
 " Linear, 67
 " of Air, 83
 " " an Area, 69
 " " Gases, 74
 " " Liquids, 71
 " " Solids, 64
 Explosion Engine, 37
 Explosions, 5
 Explosive Mixtures, 191
 Explosives, Defined, 33
 External Work, 123

 Factor of Evaporation, 157
 Fahrenheit, 13
 Feed Pump, 146
 " Water Heater, Cochran, 162
 Firebox, 149
 Fireless Cookers, 242
 Firing, 179
 Fixed Carbon, 28
 " Energy, 2, 4
 " Point, 270

Flashlights, 35
 Fog, Defined, 110
 Four-cycle Engine, 180
 Freezing Mixtures, 257
 " Point, 106
 " " Defined, 112
 " " Determined, 116
 Fuel Calorimeters, 283
 " Efficiency, 158
 " Energy of, 31
 Fuels, 27
 " Exceptional, 35
 " Gaseous, 27, 29
 " Liquid, 28
 " Solid, 27
 Fulminates, 35
 Functions of Steam Engine, 167
 Furnace, 36, 139
 " Efficiency, 235

 Gas Engine, 212
 Gas Engine Fuel, 178
 Gasolene, 37
 Gasolene Engine, 9
 Gases, Defined, 110
 Gases, Expansion of, 74
 Gauge Pressure, 130
 Generators, 4, 7
 Governing, 191
 Governor, 205

 Heat Balance, 235
 " Energy, 5
 " " Nature of, 8
 "] Engine, 37
 " Radiation Pyrometers, 282
 " Radiations, 237
 " Rays, 7
 Helium, 29
 High Explosives, 35
 Higher Fuel Value, 285
 Hot Ball, 179
 Hot Tube, 179
 Hydro-Electric Power Plant, 37
 Hydrogen, 29, 30
 " Sulphide, 29

 Ice, 102
 Illumination, 38
 Indicated Horse Power, 151, 188
 Indicator Card, Ideal, 171
 Insulation, 223, 234
 " Devices, 242

Insulation of Cold Storage Spaces, 263
 Internal Work, 123
 Ion, 118
 Iron, Oxides of, 35
 Isothermal Expansion, 74, 202

 Joule, J. P., 16
 Jump-spark, 179

 Kerosene, 37
 Kinetic Energy, 3
 " Theory, 10

 Latent Heat of Fusion, 104
 " " " Melting, 104
 " " " Vaporization, 105, 122
 Law, Boyle's, 74, 90
 " Charles', 76, 90
 Light, 237
 " Ultra Violet, 237
 " Velocity of, 8
 Lignite, 28
 Linear Expansion, 67
 Liquid Fuel, 179
 Liquids, Defined, 109, 110
 " Expansion of, 71
 Low Temperature by Mechanical Means, 258
 Lower Fuel Value, 285

 Magnesium, Oxides of, 35
 Mahler Bomb Calorimeter, 284
 Make and Break, 179
 Marks and Davis' Steam Tables, 159
 Mass, 10
 Mean Effective Pressure, 151, 288
 Measurement of Temperature, 268
 Mechanical Equivalent Apparatus, 18
 Melting, Defined, 112
 " Point, Defined, 112
 Mercury Thermometer, 270
 Methane, 29
 Mixtures, 117
 " Method of, 47
 Moisture, 27
 Molecules, 10
 Moorby, N. H., 17
 Moore Tubes, 240
 Motors, 4, 7

Natural Gas, 37
 Newton's Law of Cooling, 238
 Nitrogen, 29

Oil, 4
 " Engines, 179
 Optical Pyrometers, 283
 Otto Cycle, 180
 " Engine, 182
 Oxidation, 4, 5
 Oxygen, 29, 30

Piston, 9
 Peabody's Steam Tables, 159
 Peat, 28
 Phosphorus, 30
 Physical Mixtures, 117
 Potential Energy, 4
 Potentiometer, 282
 Powdered Fuels, 29
 Power Plant, 37
 " Test Committee Report,
 230
 Pressure Cooker, 122
 " Entropy Table, 217
 Primary Batteries, 6
 Producer Gas, 37, 182
 Prony Brake, 151
 Proximate Analysis, 28
 Pyrometer, 279, 283
 Pyrometers, Optical, 283
 " Heat Radiation, 282,
 299
 " Resistance, 276
 " Thermo-junction,
 279
 Quality of Steam, Defined, 111
 Quantity Units, 14

Radiation, 52, 223, 236
 " from Sun, 8
 Radiometer, 238
 Rankine Cycle, 170
 Ratio of Specific Heats, 201
 Rays, Ultra Violet, 238
 Regelation, Defined, 112
 Regenerative Method, 260
 Relative Humidity, Defined, 113
 Refrigeration, Household, 246
 " Mechanical, 247
 " Plant, Absorption
 Type, 256
 " " , Energy Flow
 through, 250

Reversible Processes, 211
 Reynolds, Osborne, 17
 Rowland, H. C., 16

Salts, 106
 Saturation, Defined, 110
 Saturated Steam, 111
 Sawdust, 234
 Searles Apparatus, 18
 Separating Calorimeter, 292
 Significant Figures, 309
 Solid Defined, 109
 " Expansion of, 64
 " Fuels, Classification of, 28

Solute, 117
 Solutions, 117
 Solvent, 117
 Spark, 9
 " plug, 179
 Specific Heat, 44
 " " of a Gas, 198
 Specific Volume, 130
 Spectroscope, 238
 Steam Boiler Explosion, 124
 " Cycle, 252
 " Dome, 146
 " Engine, 4, 7, 37, 212
 " Engine Functions, 167
 " Indicators, 288
 " , Quality of, 151
 " , Saturated, 103, 106, 111,
 124, 130
 " Tables, 124, 130
 " " , Marks and Davis',
 159
 " " , Peabody's, 159
 " Temperature of, 125, 130

Steel, 6
 Still-heads, 119
 Stoker, 154
 Stored Energy, 4
 Straight Line Equation, 318
 Stroke, 141
 Sublimation, Defined, 112
 Sulphur, 30
 Superheated, Defined, 111
 " Steam, 111
 " " Defined, 133
 Superheaters, 146, 150

Temperature Absolute, 81
 " of Steam, 125
 " Units, 12
 Thermal Ohms, 229

- Thermal Resistance, 229
 Thermite, 35
 Thermo-junction, 9, 288
 " " Pyrometers, 279
 Thermometer, 12, 51, 288
 " , Air, 87
 " , Alcohol, 274
 " , Calibration of, 270
 " , Gas, 294
 " , Mercury, 270
 " , Sensitive, 274
 " , Standard, 272
 Thermostats, 268
 Thompson Indicator, 288
 Three States of Matter, 101
 Throttling, 191
 " Calorimeter, 290
 Two-cycle Engine, 180

 Ultimate Chemical Analysis, 28
 Ultra Violet Rays, 8

 Vacuum Distillation, 119
 " Pan, 120

 Vapor, Defined, 110
 " Tension, 124
 " " Defined, 113
 Vaporization, Defined, 112
 Vaporizer, 179
 Volatile Matter, 28
 Volume, 94

 Water, 102
 " Circulation, 146, 166
 " Equivalent, 48
 " Rate, 159
 " Turbines, 4, 7
 Watts Indicator, 151, 288
 Wave Lengths, 237
 " Motion, 7
 Wein's Law, 241
 Wood, 4
 Work, 141
 " Defined, 2
 " External, 123
 " Internal, 123
 Working Medium, 195

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